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WATER HYACINTH AS AN ENERGY RESOURCE

A thesis submitted for the degree of
Doctor of Philosophy

by

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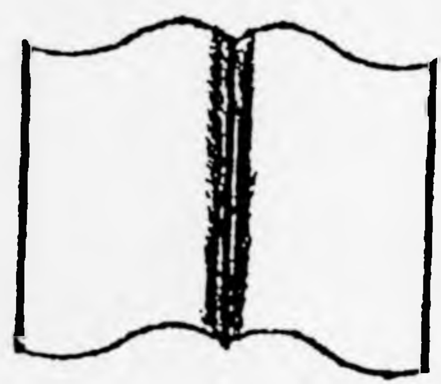
NUMEROUS ORIGINALS IN COLOUR

THIS VOLUME HAS A
VERY TIGHT BINDING



ABSTRACT

Water hyacinth (*Eichhornia crassipes*, (Mart) Solms), a floating aquatic plant, has long been recognised as a potential commercial resource but, despite many attempts, its conversion from a nuisance into an asset has not been achieved on a significant scale. The thesis is an analysis and assessment of the options for overcoming the many difficulties encountered in the use of water hyacinth. Following a literature survey, from which a process flow path for optimum use of water hyacinth is devised, the thesis leads to an evaluation of the key components of the proposed system for use of water hyacinth as a large-scale energy resource. The principle component of a system to produce energy from water hyacinth is the anaerobic digester. Trials with high-rate anaerobic digesters were conducted in Bangladesh and Thailand.

In Bangladesh, with the assistance of senior personnel from the Department of Chemistry of Dhaka University, an 8.3 cubic metre, multi-stage, upflow anaerobic digester was built within the grounds of the Housing and Building Research Institute in Dhaka. Trials with this unit, and associated laboratory work, demonstrated and quantified both the need and the scope for pre-treatment of raw water hyacinth prior to anaerobic digestion. Initial experimentation in Bangladesh laid down the foundations for an understanding of water hyacinth and led to the experimental programme performed in Thailand.

In Thailand, following an extensive search and selection of suitable juicing apparatus, a series of batch reactors were run with juice made from separate parts of the whole plant. These results were compared with each other and with a reactor running on juice made from whole plant. The conclusion drawn from this experimentation was that, when mechanically pre-treated, the root section of the plant will contribute more to gas production than will the stem portion. In many previous trials the root has been discarded because of its resistance to anaerobic digestion in a raw form.

A multi-stage upflow anaerobic digester was conceived with inclined weir plates, intended to resist blocking of the flow paths by insoluble solids in water hyacinth juice. A series of four of these units were built on a laboratory scale and trials carried out over a period of one month. These trials demonstrated that the proposal to juice water hyacinth prior to low-solids, high-rate anaerobic digestion is one that is technically feasible.

The final sections of the thesis use an economic model of the proposed system to conclude that small-scale (3 m^3 biogas per day) and medium-scale (1,000 m^3 biogas per day) utilisation of water hyacinth will be difficult to achieve in a commercial setting. Large-scale (above 100,000 m^3 biogas per day) utilisation of water hyacinth, however, is concluded to be of significant commercial potential.

DEDICATION

TO MY WIFE TUM,
MY TWO DAUGHTERS NADINE AND LALANA
AND MY MOTHER AND FATHER

ACKNOWLEDGMENTS

My primary thanks go to Terry Thomas who has managed to retain an interest in the subject of water hyacinth utilisation through many years and many operational setbacks. Without Terry's support this thesis would never have appeared.

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In Bangladesh I wish to thank both Professor Haider and Professor Mahmood for the assistance they gave in setting up the intial experimentation and pushing through against the great difficulties encountered in Dhaka. Their warm-hearted hospitality will always be remembered. Mr Hannan, from the Housing and Building Research Institute in Dhaka, provided great practical assistance in building the first unit and in carrying through the various trials performed in Bangladesh.

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With regard to the preparation of the thesis I wish to thank my father who assisted by proof-reading the raw drafts and offering suggestions on certain of the technical options discussed.

My particular thanks go to my wife who, having joined me halfway through the study period, was obliged to spend many hours of conjugal relaxation on her own. This requirement to exist in my absence extends to my two little girls, Nadine and Lalana, who very rapidly learnt the words "Dada working" through constant repetition.

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BACKGROUND

The first chapter in this thesis introduces the analytical framework around which the current research effort is structured. It concludes with a statement of the central proposition to be addressed.

1.1 WORLD ENERGY NEEDS

Both at present and in the medium-term future, biomass offers a comparatively small but commercially viable contribution to world energy supply.

1.1.1 Context of the research

The question of future energy resources is one that has directed many research efforts. There will be no disagreement with the statement that first world contemporary energy usage patterns are being substantially met by finite non-renewable resources. The exact degree to which they are finite depends upon the source of the feedstock and the conversion technology employed. Fossil fuels may reasonably be expected to decline in availability during the course of the next century as world consumption outstrips new finds. Nuclear power will follow a similar decline unless fast-breeder reactors are more widely employed. The current worldwide concern about the safety of such power generators and the effects of catastrophic accidents, as seen at Chernobyl, will only increase as more accidents occur. The next century is also the period when fusion energy may perhaps be available. The possibility of the deuterium / deuterium reaction being harnessed has offered the prospect of virtually infinite energy supplies for all mankind. This paradise scenario, however, can only be viewed as a remote opportunity and can certainly not be counted upon for future needs.

In recent books about energy supplies there has been an increased tendency to acknowledge the existence of renewable sources of energy. These are, however, usually lumped together into a single chapter with the most prominent factor emerging from their analysis being that they are not economic in comparison to the fossil fuels currently available.

This is a serious shortcoming and requires to be addressed. Coal, oil, gas and nuclear sources form the major non-renewable energy reserves. Together with hydro-electricity, the only well established commercial renewable energy source, they provide the market base for determining the cost of power. Renewable sources developed in varying degrees are solar energy, geothermal energy, wind power, wave power, tidal power, ocean thermal power and biomass. The cost of implementing these technologies at present is almost always high and payback periods are not commercially viable within realistic time frames, except in specially favourable physical or fiscal circumstances.

Table 1.1 *Current and future world energy consumption and population*

	Energy consumption 1988 (EJ)	Target energy consumption 2050 (EJ)	Population 1988 (US Billion)	Population 2050 (US Billion)
Developing countries	84	580	3.92	9.16
Industrial and former Soviet block countries	248	281	1.19	1.36
World	332	861	5.11	10.52

After Eden,RJ,1995

A further problem is that of availability versus demand. With solar, wind, wave and tidal power it is usually necessary to interpose some form of buffering between the creation and use of energy. This adds further expense and reduces the efficiency of already low levels of conversion. Geothermal power and ocean thermal power are specific to particular locations and, therefore, have limited potential for wider application.

Referring to data forming the basis of Table 1.1 (Eden,RJ,1991), the current per capita energy demand in industrialised countries is put at 230 GJ per annum and in developing countries at 22 GJ. Including the former communist block countries, total annual world energy demand currently stands at 332 EJ. It is anticipated that the major growth in demand will come from developing countries and that by the year 2050 this will rise to 861 EJ. At the same time the world population will double. In 1960 the developing countries comprised 70% of world population. By the year 2050 it will probably be between 85 and 90%. Viewed against this background the need to develop renewable energy sources becomes urgent.

Biomass, as a source of power, is currently rarely employed in an industrial society and is seriously under-developed. There are very few schemes that use this form of energy on a large scale, despite biomass energy sources being available on a worldwide basis. Low level implementation does occur in countries such as Bangladesh, where fuel wood and dried cow dung for combustion form a major segment of national power consumption, but the application of biomass for electricity generation and transport is minimal. In Europe and the USA biogas from landfill sites has found modest commercial application but often only with the support of national and local government grants. In Brazil the large scale use of sugar cane to produce ethanol as a petroleum substitute is also practised as a result of government intervention.

In a free market economy, where financial subsidisation is not permitted, the application of current renewable energy conversion technologies would rapidly decline in the short term. The challenge for technology is to overcome the problems which result in their current commercial inadequacy.

One scenario that may reasonably be expected to develop is that energy sources, rather than centralising around one particular massive and singular supply, will diversify to encompass all available opportunities. Solar energy has already found application under certain conditions in replacing batteries and it is likely that this initial inroad will expand to incorporate other applications currently met by more conventional power.

1.1.2 The potential for biomass as an energy resource

In the case of biomass, despite the low level of sophistication currently available for conversion, the potential can be readily assessed to be significant. With respect to global primary biomass productivity, it has been estimated that between 100 and 125 giga tonnes dry matter per annum is produced on land and between 44 and 55 giga tonnes of dry matter per annum is produced in the world's oceans (Cooper, 1975). Taking a figure of 17.5 MJ/kg (Slesser, 1979) for the energy content of dried biomass, the total potential biomass energy production on a global basis is between 2,520 and 3,150 EJ per year, or between 80 and 100 TW. The current world power requirement, based on oil equivalence, is put at 10.5 TW, rising to 27.2 TW by the year 2050. (Eden, 1991)

One hectare of land surface will produce varying amounts of biomass, depending upon the crop nutrient availability and other factors such as solar irradiation. Table 1.2 provides an example of selected crop productivities. As can be seen, crop yields vary significantly with type and location. The water hyacinth plant, however, far exceeds all terrestrial plants.

In the case of the anaerobic digestion of bio-matter for the formation of methane, a rule of thumb figure estimates 400 litres of biogas per kilogramme dry matter. The biogas will generally be composed of 60% methane and 40% carbon dioxide. Typically, therefore, one tonne dry weight of biomass will produce 8.4 GJ of energy in the form of methane, which represents one half of the biomass's original calorific value.

Table 1.2 Annual productivities of selected agricultural crops. (Cooper, 1975)

Crop	*Location*	*Yield (t/ha yr dry wt)*
Ryegrass	*UK*	23
Sugar beet	*UK*	23
Sugar beet	*Washington, USA*	32
Wheat	*UK*	5
Wheat	*USA*	30
Rice	*Japan*	7
Sugar beet	*California, USA*	42
Sorghum	*California, USA*	47
Oil palm	*Malaysia*	40
Sugar cane	*Hawaii*	64
Napier grass	*Puerto Rico*	85
Water hyacinth	*Florida, USA*	215

The per capita power consumption in industrialised countries, based upon oil equivalence, is 7 kW; in developing countries consumption is put at 0.67 kW. Table 1.3 expresses the land area requirement per capita to meet current levels of consumption using different crops to produce methane via anaerobic digestion. There are several levels of assumption, with regard to process conversion efficiencies, made within this comparison. The intention here is to provide an overall impression of the situation with regard to energy formation via methane. Once again, such figures clearly demonstrate the relative value of water hyacinth as an energy crop, being within the bounds of feasible supply, as compared, for example, to wheat.

In terms of biomass equivalence [One tonne biomass equivalent (tbe) = 8.4 GJ, 0.2 tonnes oil equivalent (toe)], the requirement to meet current per capita power demand is 2.5 tonnes per annum for developing per capita power demand is 2.5 tonnes per annum for developing countries and 26 tonnes per annum for industrialised countries. This is expected to remain constant in developed countries and rise to 7.5 tonnes per annum for developing countries.

Table 1.3 *Per capita surface area requirement to meet current power consumption with various crops producing methane via anaerobic digestion.*

Crop	*Location*	*Land requirement*	*(ha/capita)*
		Industrialised countries (7kW/cap)	*Developing countries (0.67kW/cap)*
Ryegrass	*UK*	*1.15*	*0.120*
Sugar beet	*UK*	*1.15*	*0.120*
Sugar beet	*Washington, USA*	*0.83*	*0.086*
Wheat	*UK*	*5.29*	*0.552*
Wheat	*USA*	*0.88*	*0.092*
Rice	*Japan*	*3.77*	*0.394*
Sugar beet	*California, USA*	*0.63*	*0.066*
Sorghum	*California, USA*	*0.56*	*0.058*
Oil palm	*Malaysia*	*0.66*	*0.069*
Sugar cane	*Hawaii*	*0.41*	*0.043*
Napier grass	*Puerto Rico*	*0.31*	*0.032*
Water hyacinth	*Florida, USA*	*0.12*	*0.013*

Taking Bangladesh as one example to put these figures into context, the area of the country is 143,999 sq km. The population density in the year 1986 was 723 per sq km. By 2000 it is expected to be 970 per sq km. The 1986 power requirement for Bangladesh in the commercial sector, excluding traditional fuels such as cow dung and collected timber, was 4,480 MW, or 0.043 KW per capita (Bangladesh Bureau of Statistics, 1987). This would have been met by 1,933 sq km of napier grass or 764 sq km of water hyacinth, equivalent to 1.34% and 0.53 % of the area of the country respectively. At a more typical developing country power consumption (ie. 0.67 kW per capita) these areas would be 15 times higher.

The problem is, of course, that the energy in biomass is not as readily available for use as is that in coal or oil. The conversion of this resource into useful energy is not yet established in a commercially viable manner for large scale and meaningful contributions to a typical social requirement.

1.1.3 Major opportunities for using biomass

Wild biomass

In theory, it would be possible to collect wild biomass for commercial energy supply, as it is widely collected for cooking fuel in rural areas of developing countries. In practice there would be significant drawbacks. The inevitably low yields would require the sequestration of larger land areas than would be necessary for an energy farm. Harvesting and transportation costs would thus be greater than for a planned cropping system. There would also be no control over aspects of growth to maximise economic returns. A further problem with the harvesting of wild biomass for energy purposes is the relationship that wild plants have with their environment. Where large scale harvesting of wild plants is performed, it is likely that imbalances will be set up within the local eco-systems. It is for these reasons that it is unlikely that wild biomass harvesting will contribute significantly to any programme of large scale energy generation from biomass sources.

Wastes

Within the definition of organic wastes, there are several large sources of biomass already recognised and currently used for energy. Domestic refuse is a major source of organic matter and its contribution to the energy requirements of industrial countries has already commenced. In the United Kingdom, for example, 28 million tonnes of domestic refuse are produced per annum (Richards, 1990). If we take an average calorific value of approximately 10 MJ/kg, allowing for 'dilution' by inert materials, this is equal to a (heat) power production of approximately 9 GW. Similar ratios are encountered on a per capita basis in other industrial countries. It should be noted that in many developing countries the waste stream is effectively recycled into the local economy at various levels by different specialised sectors of the society. In Cairo, for example, waste is separated out by approximately 20,000 inhabitants of one particular area in the city where all waste materials are deposited. This separation continues right down to the organic matter which is retained as feed for pigs. The introduction of energy from domestic waste schemes into an economy such as that in Cairo would inevitably produce less overall benefit than the current system.

In Britain there are a number of large waste biomass streams capable of being burnt or digested into biogas for energy creation. The most important of these are sewage, livestock waste, crop wastes and industrial wastes.

Six million tonnes of sewage are produced annually in the UK. When this is added to approximately 46 million tonnes of livestock waste, the total rises to around 52 million tonnes (Horton, 1976). It has been suggested, perhaps a little optimistically, that methane obtained from this source of human and animal excreta could replace up to 25% of the UK's annual gas requirement (Horton, 1975). Biogas produced from the anaerobic digestion of human and animal waste has a calorific value of typically 25 MJ per cubic meter. Productivity rates are 80 m^3 biogas per wet tonne for cattle manure, 250 m^3 for pig manure and 360 m^3 for poultry manure.

Agricultural wastes include such items as straw waste, wood waste, sugar cane bagasse, potatoes, sugar beet and vegetables. It has been estimated, for example, that within the EC 1,600,000 tonnes dry matter per year of residues are produced from the processing of potatoes. From the processing of sugar beet the green residues amount to 13,528,000 tonnes dry matter per year and vegetables in general produce 3,697,000 tonnes dry matter per year (Palz, 1980). Taking a calorific value of 17.5 MJ per kg and assuming a 60% conversion efficiency for biogas production in an anaerobic digester, the combined value of these three waste materials in terms of energy is approximately equivalent to 6.26 GW on a continuous power supply basis.

In the case of straw, which has an air dried calorific value of about 15 MJ per kg, it was estimated in 1978 that there were 86,393,000 tonnes of cereal straw produced in the European community. This represents a renewable energy resource of approximately 41 GW on a continuous basis (Palz, 1980). It has been further estimated that between 4 and 7% of the energy content of straw might be needed for harvesting and transportation (Morris, 1977).

Industrial waste covers materials left from the production of commodities, such as beer and paper, where large quantities of organic matter require to be treated prior to disposal.

The use of waste materials within industrial societies is one which has received a great deal of attention since 1973, and in many cases energy recovery has become a standard application. Large scale municipal incinerators are an example of the application of energy recovery from domestic waste. It is to be expected that energy will increasingly be recovered from organic waste streams.

Cultivated biomass

It is within the area of cultivated biomass that the greatest contributions to human energy requirements have been made and are likely to be made in the future. The most ambitious and large scale biomass energy programme which is currently operating is that in Brazil. The project is based on the extensive cultivation of high yielding cassava and sugar cane crops. These two primary feedstocks are supplemented with sweet potatoes and babacu nuts. Following fermentation and distillation, the final product is ethanol intended for use as a motor fuel constituent, up to a level of 20% in standard engines (Boyles, 1984). Specially adapted engines, a large part of the Brazilian fleet, can handle up to 80%. The objective is to make appreciable savings in petrol consumption and offset the import of oil. In 1976 Brazil was paying more for its imported oil than any other developing country in the world. The target of 3,000,000 m^3 per annum of anhydrous alcohol was estimated as necessary to meet the internal demand.

The concept of intensively managing densely planted trees under short rotations as an energy crop has been receiving increasing attention. This is described as coppicing and was widely practised in certain parts of the world until about 1900. Several species have been identified as especially suitable for this process, including eucalyptus, alnus, sycamore and tulip poplar, giving rise to dry weight yields of 12.5 - 32.5 tonnes per hectare per year. A lot depends on the particular species selected and the location in which it is grown. It is, however, envisaged that yields will be doubled in the next twenty-five years with improvements in technique. This advance may be offset by the need to have greater additions of various fertilisers.

Both fresh water and ocean farming have been the recipients of a great deal of research effort in the United States. The growth of both microscopic and macroscopic algae, as well as water hyacinth, are being investigated. They produce considerably greater yields than land-based plants. In California, where work is being carried out on algal-bacterial systems, the solar radiation available all year round is sufficient to ensure that the operation is virtually a continuous one. A 1,000 m^3 pond in California produces annual algal yields of approximately 50 tonnes dry weight per hectare, with the predominant genera being the green *Chlorella scenedesmus* and *Euglena*. Although mixing is required to prevent cellular sedimentation, the major drawback to the process is the technique required for harvesting. With a pond concentration of 200 mg per litre, it has been estimated that the minimum electrical power requirement per tonne of dry weight algae is 10 MJ per kg dry weight of algae, ie over half its calorific value, for the centrifugation stage alone (Uziel, 1975).

The large scale cultivation of macroscopic marine algae for energy production has also been investigated in the United States. Two red seaweeds, *Gracilaria sp.*, and *Hypnea musciformis* have been investigated in 600 litre growth tanks. Both species attained yields of approximately 60 tonnes per hectare per year dry matter (Lapointe, 1976). One interesting development from the work on seaweed was that the investigators subsequently arrived at the conclusion that the major contribution that may be made from such aquatic systems was in the form of substitution rather than energy production. Instead of using anaerobic digestion for methane generation, the algal biomass was believed to be preferably used for protein production, fertiliser production, drugs and colloids, as well as components within advanced waste water treatment and waste recycling processes (Goldman, 1978). A separate study on the West Coast of the United States has been based upon the production of the giant kelp *Macrocystis pyrifera*. In this case an area of 8,000 hectares at an ocean depth of 12-25 metres is targeted as the growth area. Photosynthetic efficiencies are expected to be high with an annual dry organic matter productivity in the range of 50-80 tonnes per hectare. (Wilcox, 1976).

One of the most productive of aquatic plants is the water hyacinth with annual productivities around 200 tonnes per hectare. Its potential for utilisation has not gone unnoticed. A great deal of research has been invested in pursuing the goal of large scale employment of water hyacinth for energy production and for other purposes. Despite considerable effort, this goal, however, has yet to be achieved. Much previous work has concentrated on individual stages of the plant's growth and use and considered these in isolation. The economic exploitation of water hyacinth involves a number of inter-related stages, each one of which, if not properly and efficiently performed, may result in the overall process failing. It is the analysis and refinement of the overall system which forms the basis for the current work.

1.2 BACKGROUND TO WATER HYACINTH

1.2.1 History of the spread of the water hyacinth

Water hyacinth,(*Eichhornia crassipes*, (Mart.) Solms) belongs to the family Pontedeiacea, named after J.A.Fr.Eichhorn (1779-1856), a Prussian Minister of Education. An example of its prodigious growth may be seen in the case of the Sudan. When first recorded in 1955 it was occupying a stretch of the River Nile in the North of the country. Within four years it had infested over 3000 km of waterway, including several lakes. This situation, as recorded in 1962, is very similar to the current situation, in spite of a control programme having been operational since this former date.

Water hyacinth began its journey around the world in 1884 when it was taken from its natural environment in the waters of the Orinoco River in Venezuela, where it lived in balance with the environment, kept in check by various types of fish, viruses and insect predators, and was brought by members of a Japanese contingent to the Cotton States Exhibition held in New Orleans. It was brought because of its beautiful lavender flowers. There, as history has it, it was handed out to visitors at the Japanese stall as a souvenir. Chlora (1909) states that the plant was:

> "shown then as an exotic plant which readily made friends on account of its beautiful bloom and the little difficulty exposed in growing it. From New Orleans some of the plants were taken to the surrounding parishes and cultivated in ponds and gardens as admirable aquatic specimens. It is supposed that they were passed out, or probably dumped, in some nearby streams ...."

Within only 11 years of the Exposition a water hyacinth raft 100 miles long was discovered on the Saint John's River in Florida.

From the Cotton States Exhibition water hyacinth has progressed around the world by the efforts of individuals enchanted by its flower or botanists interested in having examples to hand. The wife of King Rama the fifth of Thailand, for example, brought water hyacinth to Thailand from Java in 1901, hence its Thai name "pak top chawa"; vegetable from Java. It was carefully cultivated in ponds within the palace grounds but by some means, possibly flooding, it escaped into the surrounding waterways and is now a major pest in Thailand requiring extensive treatment to remove it from important waterways. Canals and rivers of lesser importance are left as green mats. In 1913 the Water Hyacinth Control Act was brought into force in an attempt to control its rampageous growth. This act is still in effect but has fallen into disuse as the plant is now accepted as a part of the local environment. It has become a tradition in certain areas to carry out major cleaning efforts on the occasion of the current King's birthday. Experimentation by the present researcher at Mahidol University in Bangkok was interrupted when the ponds within the University ground were cleared of all their water hyacinth. These were deposited on the banks to rot. As a feature of water hyacinth, its rapid growth rate ensured that within a few days there were new sources of feedstock for the experimental process in exactly the same locations.

In India the plant is believed to have been brought to the province of the then Bhangal, which is now Bangladesh, sometime between 1888 and 1900. The wife of a sub-divisional officer, with the family name Morgan, at the Narayenganj near Dhaka, requested that her husband bring her the plant to decorate her gardens. The flower of the water hyacinth, as a result, is sometimes referred to as Lady Morgan's Flower by the Bangladeshis. In Bangladesh it can truly be said that a result of Lady Morgan's horticultural interests has been the devastation of the waterways of Bangladesh. It is reported that huge mats of floating water hyacinths are carried during the flood into rice paddies where the receding waters dump hundreds of tonnes of the plant onto rice growing land. As in many other countries around the world, aquatic weeds clog up irrigation canals and pumps, make fishing difficult, make passage through waterways sometimes impossible, interfere with hydroelectricity production, increase waterborne disease, block drainage systems and thereby worsen the effects of flooding and cause problems for rice farmers when, during the rainy season, their fields are smothered in great rafts of matted weeds. The water hyacinth often becomes so abundant in natural streams that it impedes run off and causes backup and flooding. The plant is occasionally piled up on the upstream side of bridges in sufficient quantities to overturn them in flood conditions.

1.2.2 The nature of current problems

The problem of aquatic plant infestations in tropical and semi-tropical countries is not a new one. It has been a recognised phenomenon for many years. However, with increased levels of use of water resources, the problem is becoming an expensive drain on many developing country finances. In the Sudan, for example, the cost of keeping waterways clear for traffic on the river Nile and its tributaries was to the order of three million dollars per annum in the late 1970's.

It has been estimated that within approximately 50 tropical and sub-tropical countries the problem of water infestation with aquatic weeds is being dealt with daily by millions of people as they attempt to carry out tasks associated with waterways. The problem does not simply stop at the level of individual difficulty. Hydroelectric schemes have been reported to be losing potential power generation capacity as a result of the increased rate of loss of water caused when a water area is covered with aquatic plants. Evapotranspiration can cause water loss rates to double, compared with pan-evaporation losses alone.

There are many different types of aquatic weed which have to be contended with. These are generally categorised as floating, emergent or submerged. Those most commonly found of the floating type are water lettuce (*Pistia stratiotes*), salvinia (*Salvinia spp.*) and water hyacinth (*Eichhornia crassipes*), the latter being the subject of this thesis. The roots of these plants hang in the water and are not attached to the soil. As will be explained in more detail later in the text, water hyacinth can also become rooted in shallow water when it would technically be classified as emergent. Emergent weeds are those that are rooted but extend above the water surface. Cattails (*Typha spp.*), papyrus (*Cyperus *papyrus*), the bulrush (*Scirpus species*) and the reed (*Phragmites communis*) are examples of this type. Submerged weeds are those which grow below the surface. They can form a dense wall of vegetation from the bottom to the water surface. Examples are hydrilla (*Hydrilla verticillata*) and water milfoil (*Myriophyllum spicatum*).

1.2.3 Growth rates

Water hyacinth is particularly notable because of its enormous growth rate. Enlarging upon data provided earlier in this chapter, there is a considerable body of knowledge from which to draw. For example, harvesting studies demonstrated that, over the seven month growing season that exists in Florida, USA, 3,080 wet tonnes or 154 dry tonnes can be obtained per hectare. Rates of 800 kg of dry matter per hectare per day were recorded (Wolverton, 1979a). Sugar cane, which has been considered as a major candidate for large scale bioconversion, can produce 64 tonnes/hectare/year dry matter.

Numerous researchers have analysed the growth rate of the plant. By and large there is broad agreement on the quantities of biomass being produced. Mass doubling times between six and ten days are reported by researchers from the southern United States to Thailand. The exact patterns in which growth occurs depends very much on the parameters surrounding the growth situation. Where the water level is low it is possible that water hyacinth roots might reach down and anchor in the mud at the base of the waterway. This results in a particular type of plant growth. Where the water is fast moving and deep, it is found that the bulbous floats at the base of the leaves will tend to be larger in order to steady the plant in such water. Where the water is still and deep, it is often found that the dense matting results in the floats being of less importance than the survival of the plant and the growth of the stems is consequently longer. In thick growths of water hyacinth there is often competition for available light and the leaves will rise higher and higher into the air to gain advantage from the third dimension. If the water is particularly nutritious, it may be found that the increase in plant growth will be significant with a major proportion contributed from the root section of the plant. Indeed the root section may contribute up to 40% in certain cases. Plant growth in individual locations must be analysed on the basis of specific circumstances. In a situation where utilisation of the plant is being considered it will be necessary to determine which sort of growth is desirable and arrange the cultivation and harvesting in such a way that the desired growth is maximised. The stems, for example, often have a higher proportion of lignin within their structure. Work carried out as part of this thesis has demonstrated that the stem is also less productive in terms of biogas. Therefore, where biogas is the main objective, a growth and harvesting regime which minimised stem length and maximised leaf area would be desirable. The leaves are found to be very productive in terms of biogas production.

There are a number of key constraints to the growth of water hyacinth which, fortunately, have prevented the plant from taking over the whole world. Primary amongst these are the fact that below a temperature of approximately 20°C all plant growth stops. The second major constraint to growth is that any salinity in water will kill the plant immediately, so water hyacinth does not survive in estuaries where fresh water is mixed with tidal sea water. A further factor which has been found to significantly influence the growth of the plant, is relative humidity. Where higher relative humidity is encountered, rapid growth may be expected to take place, the other two constraints being satisfied.

Set against these limitations is the fact that water hyacinth appears to thrive on poisons that may be considered toxic to other forms of life. Water hyacinth will absorb and ingest cadmium, nickel and silver deposits and has been widely used as a method of waste water purification. The upgrading of sewage lagoons in many parts of the world has been achieved by use of water hyacinth.

1.2.4 Control of the plant growth rate

Initially, when water hyacinth was found to be blocking vast tracks of water and clogging up canals and other waterways in the USA, the first remedy attempted was poison. Sodium arsenate was used in an extensive programme but abandoned because this chemical posed the possibility of poisoning live stock and humans. From 1887 the United States Core of Engineers has attempted, with moderate success, to keep the waterways in infested areas open to navigation. As a result of this programme, a wide variety of mechanical devices has been developed for collecting and disposing of the water hyacinth. These include the bank depositing machine, the crusher and the saw-boat (Army Corps of Eng.,1946). Each of the methods employed has resulted in some degree of success. The primary objective has usually been to keep waterways open to navigation and this is normally achievable where the requirement is essential. The wider problem of preventing and controlling the growth of water hyacinth in areas of low navigational importance is still a subject of intense investigation.

There are three types of control available:

i mechanical
ii chemical
iii biological.

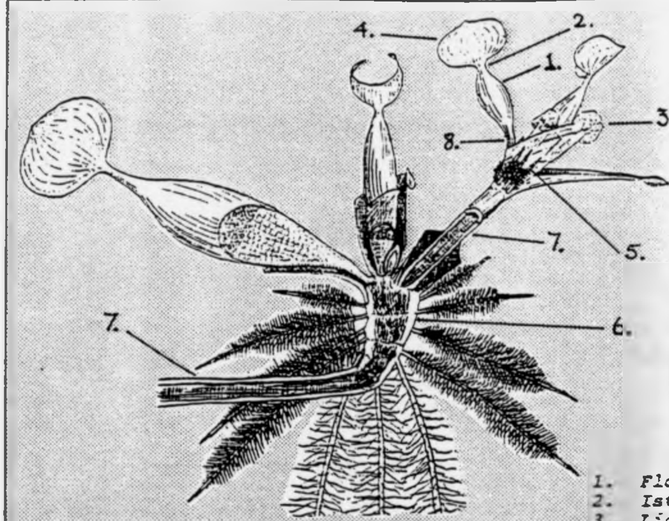
Mechanical and chemical methods have been employed for many years as referenced above, with varying degrees of success. The great hope for the future is within the realms of biological control methods. The problem with mechanical and chemical control is that they require to be repeated at regular intervals to achieve any benefit and do not offer the possibility of a long term stable reduction in the growth of the plant. Biological methods in contrast rely on the introduction of natural predators of the water hyacinth plant. A good deal of research and investigation is required to properly establish the criteria that can be employed for introducing weevils and other such pests into a new environment. The fear is that such introductions may not only be interested in devouring water hyacinth but may turn to other harvested crops with devastating effect. New techniques for making such introductions have been established in recent years and there is a growing catalogue of success within this area. It is to be expected that the growth of water hyacinth may safely be controlled in future years without the associated destruction of desired crops (Bennett, 1983).

1.2.5 Conflict between control and utilisation

The problem of conflict between control of the plant and utilisation is one that has been addressed for many years. Writing in 1920 Buckman concluded that:

> "No commercial utilisation of the hyacinth on any scale likely to be a factor in a campaign for eradication or control is to be expected."

Whilst this position is subject to minor modification in view of the work that has been carried out on utilisation, it is certainly without doubt that the benefits to society at large would be greatly enhanced by the eradication of water hyacinth rather than its commercial exploitation. The proposals as investigated in this thesis lead to the inevitable conclusion that large-scale utilisation will only be realistic with carefully managed growth. Such growth will not take up the myriad situations in which water hyacinth, growing wild, is damaging commerce and trade. It is, therefore, inevitable that any scheme of utilisation will have to face the reality that there will be natural predators to attack the harvest. This is a situation that is commonly encountered with all types of other harvested crops and it should not jeopardise the possibility of using water hyacinth. Indeed, if anything, should careful control methods be introduced, it will be possible to identify clearly the threat to the water hyacinth crop and devise methods for preventing destruction of the plants desired for harvesting.



1. Float
2. Isthmus
3. Ligule
4. Pseudolamina
5. Root
6. Rhizome
7. Stolon
8. Subfloat

Figure 1.1 Cross section of a water haycinth showing vegetative structure. (After Penfound, 1947)

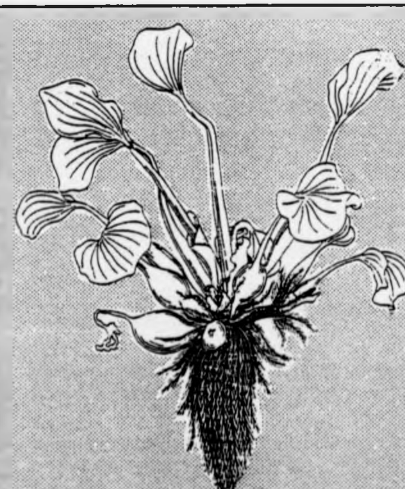


Figure 1.2 Plant from dense mat in mid-summer with necrotic float leaves (formed in early spring) and central, elongate leaves (formed after crowding occurred). (After Penfound, 1947)

1.2.6 Description of the plant

At this stage in the thesis, in order to provide additional background to the unusual nature of the water hyacinth plant, a brief description of its appearance and relation to its habitat will be provided. Additional descriptive information is included in Appendix 1 of this thesis.

Physical appearance

The mature water hyacinth plant has been recorded as having various forms of growth depending upon the circumstance in which the growth takes place. All plants, however, consist of the same components; these are roots, rhizomes, stolons, leaves, flowers and fruit clusters (see Fig.1.1).

The water hyacinth leaf has been the object of much discussion and its unusual characteristics were noted very early after its arrival in the United States (Oliver, 1894). When fully exposed to the sun, all of the leaves will develop swollen portions of the petioles, commonly referred to as floats. These float leaves consist of membranous ligules, a sub-float, a float, a tenuous portion between the float and the blade and the blade (see Fig.1.1). The blade has been noted not to be a true lamina, but actually an extension of the petiole (Arber, 1920). Under crowded conditions, however, no float is produced. The petiole on the nearly vertical equitant leaves narrows gradually from the base to the pseudolamina (see Fig.1.2). A similar type of leaf is produced on plants which become rooted on land.

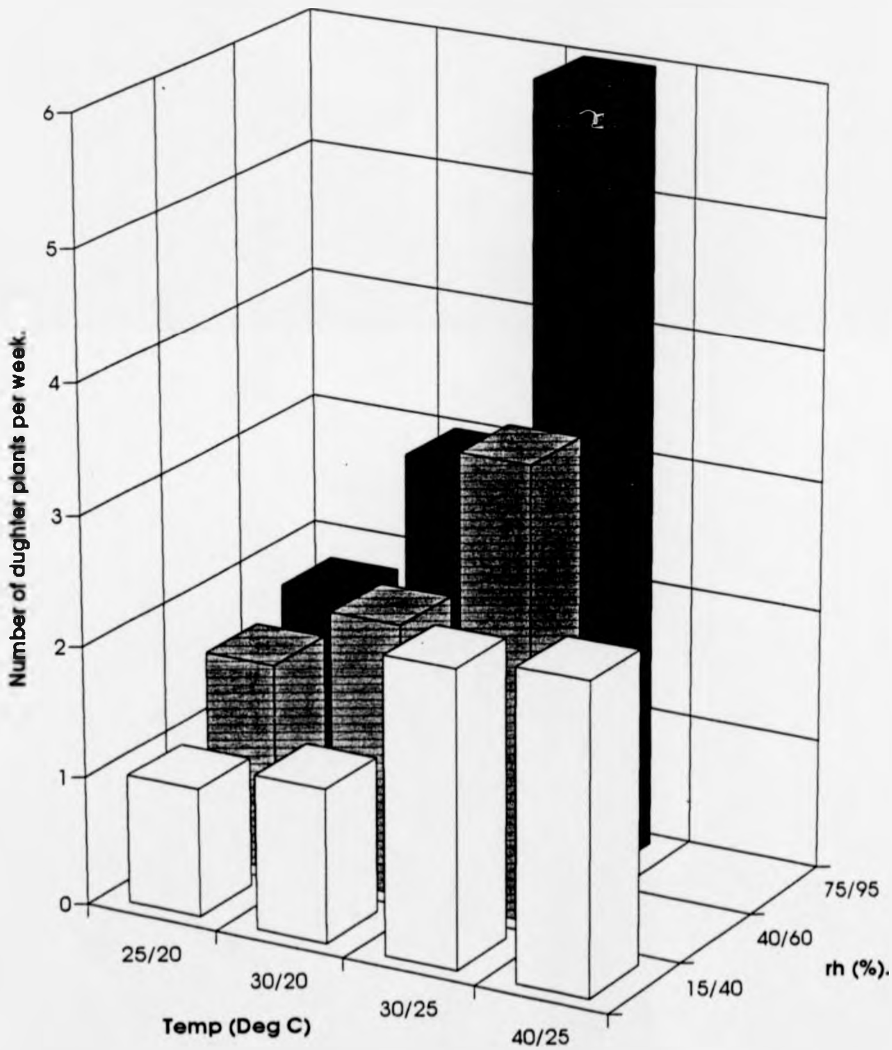
At the start of the growth season, where in various parts of the world this is clearly differentiated, plants will be found to possess float leaves on the peripheral portions and equitant leaves near the centre of the leaf cluster. In general the float leaves are disposed in a nearly horizontal position (15° to 45°) whereas the equitant leaves approach the vertical (75° to 90°).

Water hyacinth cannot survive water temperatures higher than 34°C for more than four or five weeks. On the other hand, freezing water will not necessarily kill the plant, unless the freezing water temperatures are held for an extended period. At -8°C the plants will be completely dead after 12 hours, whereas at -6°C the plants will be completely dead after 48 hours, at -3°C and 1°C the leaves will die off but re-sprouting will occur when the ambient temperature increases.

Ambient factors effecting growth rate

The importance of relative humidity and ambient temperature on the

Figure 1.3 Daughter plants production per week in relation to day and night values of climatic factors (Freidel, 1979).



growth rate of water hyacinth has been studied in the Sudan (Philipp, 1983). This work indicated a strong correlation between growth rate, ambient temperature and relative humidity. Both relative humidity and ambient temperature had a significant effect upon growth rate (Figure 1.3). Under the most favourable conditions (40°-25°C air temperature, 75%-95% relative humidity (the range representing day and night values) the growth rate indicated a production of daughter plants of six per week. This exceptional figure would demonstrate the maximum growth rates that might be achieved under carefully controlled conditions. Observations made during the rainy season in the Sudan indicated that there was a greater correlation between high relative humidity and growth rate, than between ambient temperature and growth rate. In practice, in natural conditions, the highest reproduction rate measured in the Sudan was 2.7 daughter plants per week (Freidel, 1978). There may be some scope for considering whether or not the use of green house covers may be worthwhile in increasing the plant growth rate.

The relationship between growth rate of the plant and oxygen tension is one that is worthy of note. In a pool of water with an oxygen tension averaging 0.8 ppm it was noted that growth was very sluggish and that the plants that developed were sickly. By contrast in pools with an oxygen tension in the range of 3.5 to 4.8 ppm, plants experienced rapid colonisation. It was deduced that low oxygen tension was responsible for the poor health and the poor vegetative reproduction of water hyacinth in the pool with the low oxygen tension. (Penfound, 1947)

Reproduction

The water hyacinth plant has two principal modes of reproduction: by vegetative reproduction and by seed. Vegetative reproduction is the dominant mode. Vegetative reproduction involves the growth of daughter plants from the parent plant by means of extending the stolon and a separate plant growing at the stolon tip. As the number of daughter plants increases the links between the plants break and the plants may float apart. In dense mats the links may remain in place, although these are generally easily broken. In experimental work carried out in Florida, (Penfound, 1947) the number of daughter plants was found to double in periods of between eleven and fifteen days. A calculation made by these researchers indicated that over a growing season of eight months, one plant will produce approximately 65,500 daughter plants. By contrast in the Sudan (Philipp, 1983) calculations made on the basis of work made by Freidel (1978) suggested that in one year one plant could lead to the production of 140,000,000 daughter plants, if other factors such as density, disease, nutrients and parasites were not limiting. This number of plants would cover an area of approximately 140 hectare with a fresh weight of approximately 28,000 tonnes.

In comparison with vegetative reproduction, reproduction by means of seed is not significant. Over the course of one year in Sudan, it was found that one plant would produce approximately 100 seeds. The contribution of the seeds, however, is that they remain viable over several years and will regenerate at any time where suitable conditions occur. This means that seeds may lie dormant in dry soil and sprout in periods of heavy rain. It is for this reason that attempts at mechanical removal of the water hyacinth plant have often proved to be unsuccessful.

It has also been noted that the rhizome crown will re-sprout should the water hyacinth plant be cut up by choppers or some such dissecting operation. In the United States attempts at controlling water hyacinth were made with a saw boat. A saw boat would drive up and down the water hyacinth infestations and cut the plant into shreds. Unfortunately, it was found that the segmented material from these machines re-sprouted abundantly whilst at the same time chopped sections of the plant remained afloat for periods of up to six months. In one experiment ten plants chopped in a manner similar to a saw boat resulted in the re-sprouting of 20 new plants (Bagnall,1974).

A moderate water hyacinth infestation causes relatively little damage in the habitat conditions of an area. With complete coverage, and especially when a dense turf or raw peat is formed, the changes in physical factors are profound. If the habitat conditions under a closed mat of water hyacinth be compared with those in open water, the surface water temperature is more uniform, the acidity is higher, the carbon dioxide is higher and the amount of oxygen in the water is much lower (Lynch, 1947). It was noted that in open water an average pH of 7.2 would be found, whereas the water in or near mats of water hyacinth are usually acid with a pH between 6.2 and 6.8. With regard to oxygen, the presence of a dense water hyacinth mat will reduce the oxygen tension to less than 0.1 parts per million. The reduction in oxygen is due to the decay of dying root and leaf portions from the water hyacinth plant. This is particularly notable since relatively few fish can tolerate oxygen tensions as low as 1 ppm and this will, therefore, mean that most fish will be excluded from waters that possess closed mats of the plant.

1.3 WATER HYACINTH AS AN ENERGY RESOURCE

With the advent of large scale programmes for the introduction of anaerobic digesters into rural communities in India and China, the possibility of using water hyacinth as a supplement to agricultural wastes has often been suggested. Several research programmes have been instigated by various world and national bodies into this possibility (CSC,1983) although no serious in-roads to practical energy utilisation have been developed as yet.

1.3.1 Water hyacinth

Water hyacinth, as a rapidly growing aquatic water plant, has been widely recognised as a resource by many researchers and industrialists. It has not, however, reached any significant level of application save in a few locations in the world as a feedstock for making souvenirs for the tourist industry, (eg. baskets and mats fabricated from the dried stem of the plant), or as a localised cattle feed. Its real potential as a feedstock into large scale industrialised processes has not been realised.

Water hyacinth has been demonstrated to be ideal for the biogas production process. The carbon to nitrogen ratio of the plant indicates that no additions should be required. Experimentation carried out within the scope of this research project confirms this to be the case. The principle stages in the conversion from harvested plant to the product gas are well understood. It is considered by many researchers that biogas offers the most immediate possibility for application.

Water hyacinth has an energy content of 7.6 MJ per kilogramme dry matter (air dried with 11% moisture content). Typically one hectare of standing crop will have a dry weight density of 15 tonnes/ha, giving an energy content of 114 GJ, equivalent to approximately 2.7 tonnes of oil. The plant has a prodigious growth rate. It has been estimated that one hectare, over a growing season of seven months, can produce the equivalent of 40 tonnes of crude oil (Thomas, 1990).

1.3.2 Anaerobic digestion

The normal method for obtaining energy from a wet biomass like water hyacinth is anaerobic digestion. (Other methods are discussed in Chapter 2) In the last ten to fifteen years anaerobic digestion has been in receipt of substantial and detailed investigative analysis, leading to a greater understanding of the transformations occurring. The biochemical processes were poorly understood and it is for this reason that early projects to institute wide scale application of anaerobic digestion were often unsuccessful. Another major difficulty, that is only now being overcome, was the high retention time of the organic matter in the anaerobic digester and the associated high capital cost. Typically, batch anaerobic digesters have required a forty to sixty day retention time. Intermediate technologies have been developed to build large-volume low-output digesters, but the work required in operating such a system and the many possibilities for failure have proved to be barriers that many operators have found difficult to overcome.

Within the last ten to fifteen years, research has been concentrated on increasing the rate of the anaerobic digester reactions. Such high-rate reactors are bringing closer the possibility of using biomass as a source of energy. High-rate reactors fall into two categories with respect to feedstock composition: the low-solids reactor, which processes a feedstock with a high moisture content, typically 95-98%, and the high-solids reactor with a feedstock moisture content in the region of 50-60%. The increase in the speed of reaction results from optimising the critical path reactions. Primary amongst these reactions is the rate of growth of the methanogenic bacteria. High-rate processes maximise contact between methanogenic bacteria and biomass feed by mixing and circulating the digester contents, whilst at the same time minimising the wash out of bacteria. The reason that digesters have historically required such high retention times is because the growth and spread of methanogenic bacteria into new areas of biomass feedstock is slow. In the absence of any mixing, the physical transport and contact processes do not occur.

In the case of water hyacinth, we have a rather specialised application for the new high-rate anaerobic digestion processes. Water hyacinth has a very low solids content, typically around 5%, and would appear to fit comfortably with low-solids, high-rate digestion processes. In practice however, the water hyacinth plant has a high fraction of lignin. This lignin binds and layers the digestible biomass within refractory units. The lignin also interferes with low-solids digestion processes which require a ready flow and transport. It is a common experience for researchers working with water hyacinth that in the initial stages of anaerobic digestion the plant will float. After the initial decomposition of the pockets of air within the plant, notably the petioles, the plant will sink. This condition of either sinking or floating has created problems even within simple batch reactors where a batch load of water hyacinths will initially float and not digest and then, once it has decomposed, will sink and block the further movement of any matter by sitting in the base of the digester.

High solids anaerobic digestion processes are similarly fraught with difficulty. It has been found in practice that high solids processes generally require a higher level of energy input per unit volume. They are being employed in systems where the energy input cost may be set off against other considerations. Solid industrial effluents, such as potato peelings, as well as municipal refuse, fall within this category. In both cases the cost of disposal of the organic matter may be minimised by reducing its volume. In the case of water hyacinth, where the objective is not organic matter volume reduction but resource utilisation, the input of energy to the process must be minimised.

1.3.3 Juicing

With this background in mind, the possibility of extracting and separating the largely soluble and readily digestible proportion of the water hyacinth from the more refractory and less amenable proportion has been developed as a principle theme within this thesis. 'Juicing', as this process is described, offers the possibility of maximising the economic return on various different fractions of the water hyacinth plant. The liquid portion of juiced water hyacinth appears to be amenable to low-solids, high-rate anaerobic digesters in that the opportunity for blocking and causing difficulty within the reactor is reduced by the removal of lignin. The lignin itself has a value as a byproduct and by separating it at the start of the process its accessibility and usefulness is increased. This thesis has, therefore, been developed around the theme of juicing water hyacinth and investigating the possibilities for utilisation and return on all the various components of the plant.

1.3.4 Scale of the opportunity

In order to gain an initial impression of the scale of the opportunity and, therefore, the seriousness with which the subject should be addressed, one may look at a particular situation in Bangladesh. The water hyacinth plant is recorded to have a doubling time of six days. It is reasonable to assume on the basis of information available in the literature that from a typical pond of one hectare a harvest of two hundred tonnes dry matter per annum may be achieved. With a typical conversion to biogas of 450 m^3 per tonne, the annual production of biogas from a one hectare pond will be 90,000 m^3. Converting this to a power figure, the rate of energy production from one hectare will be 60 kW thermal. An area of fifty hectare would, therefore, be adequate to generate one megawatt of electricity. This is comparable with the area of ground required to produce one megawatt of electricity from a landfill site producing landfill gas. Such schemes in Europe and the United States have approached the status of commercial processes and it is not unreasonable to consider that such applications may reach a similar level of application within tropical countries.

The conversion of biogas to electricity for its use in other processes is well understood. Biogas from landfill sites is widely employed to fire industrial engines, both of the spark ignition and dual-fuel variety. Gas turbines have also been employed with biogas fuel to produce power. Schemes around the world have been set up to use biogas as a source of commercial energy to power vehicles. With a moderate amount of gas clean-up the energy content of biogas may be increased to equal that of natural gas and injected into natural gas pipelines. Once again such schemes are achieving wide application around the world.

The key objective of linking the growth rate of water hyacinth with a suitable application has not yet successfully been achieved and widely applied. The opportunity is abundantly clear. The problems and difficulties which are encountered are equally manifest. For this reason the assessment of systems to exploit the water hyacinth plant are a principal concern of this thesis. It is not, however, intended to evaluate in detail the questions associated with socio-economic stability. The contemporary political situation of Bangladesh, and indeed many tropical third world countries, is a matter which falls outside the current evaluation. The difficulties encountered in applying technologies in a commercial and viable manner are analysed where relevant. For example, in Bangladesh water hyacinth is currently regarded as an unwelcome pest. It has been noted, however, that once the plant has found a use it immediately assumes a value. A typical case was encountered where one household decided they would fill in a large hole on their property by collecting water hyacinth and allowing it to decompose in the hole, thus building up an organic base for the growth of crops. Once it was recognised by other members of the village that water hyacinth had acquired a use it became necessary to purchase the plant in order to continue filling the hole. As a result of this the hole filling operation stopped and the unwelcome weed remained un-disturbed.

On a technical level the principal obstacle, as referred to above, is the question of retention time. In order to obtain 60 kW of thermal power from one hectare of plant employing established and traditional biogas production technologies, it would be necessary to use an anaerobic digester with a volume of around 400 to 600 m^3. It is clear that such a large volume, sealed to prevent the ingress of air or the egress of biogas, would be very expensive and could not be justified by such a small gas productivity. The current research is aimed at investigating the possibility that using juice as the medium for converting biomass into biogas would reduce the reactor size to approximately 10 m^3.

1.4 OTHER USES OF WATER HYACINTH

A recurring theme of this thesis is that the most promising single benefit to be obtained from water hyacinth is energy, but that the economic viability of utilisation often requires other product streams to be developed.

1.4.1 Background to utilisation

The possibility of using water hyacinth has been a subject of great interest from the earliest days of its appearance in western societies. An area of particular interest has been its use to upgrade and improve waste water treatment systems. The scope for using water hyacinth has steadily increased and in certain parts of the world water hyacinth is earning income for sectors of the community. In Bangladesh during any period of great flooding, water hyacinth provides a source of nutrition for cattle and other livestock that may be stranded on high ground by the onrush of flood water. This has probably been the situation from the moment that water hyacinth arrived in Bangladesh. Despite the suggestions that large scale utilisation may be viable (Lecuyer, 1976) no large scale utilisation has been instituted. The reasons for this are numerous and diverse. In almost every direction in which utilisation appears to be a possibility there is some overwhelming disadvantageous factor that ensures that utilisation cannot be accomplished. In the case of weaving souvenirs in Thailand, for example, anyone who purchases such items will rapidly discover that the strength of the woven material is inadequate for any but the lightest of applications. A handbag, however attractive and utilitarian, will rapidly fall to pieces if any items of weight are placed within it.

1.4.2 Uses of fibrous materials

The use of water hyacinth as a source of fibre has usually ridden on the back of some other process, except in unusual cases such as, mentioned above, basket weaving in Thailand. The possibility of combining juicing with the utilisation of fibre is one topic of investigation within this thesis. Previously within this field there has been very little work carried out. The possibility results from the high lignin and cellulosic fibre within the stem. Both the leaves and the root portion of the plant would not contribute significantly to the production of fibre.

Employing water hyacinth as a feedstock for paper making is another area that has been a subject of considerable research. Water hyacinth paper and board is in fact manufactured and used in certain parts of the world. However, it is found that it is of very low quality unless mixed with a large proportion of waste paper.

Water hyacinth has found numerous small-scale applications from table mats to handbags. Its use has been widespread if not large scale. In India one project was encountered which had used water hyacinth for making table mats and purses. In this particular case the preparation of the feedstock was not properly thought out and it was found that the products tended to rot after a relatively short time. The project in Thailand is more successful and the products appear to have no problem with rotting. As mentioned above the problem is one of strength. The water hyacinth fibre, whilst adequate to support the integrity of the manufactured item, appears not to have sufficient strength to survive for any great length of time. This makes them ideal for the tourist industry where souvenirs are not in general expected to experience heavy duties, or to last for extended periods of time. In this niche market, the product has gained the status of a commercially viable venture.

1.4.3 Fertiliser

It is likely that in some settings the value of the fertiliser produced from the effluent out of an anaerobic digester may have a greater value than the biogas. This is certainly the case with anaerobic digesters fed with cow dung. The volumes of gas produced daily are small in comparison to the volumes of the digesters employed and the gas has utility only for cooking and periodic lighting. The effluent from the digester, however, is fairly substantial in terms of quantities of fertiliser. In the case of water hyacinth the plant is renown for its ability to take up pollutants from waste water. Therefore, it is reasonably certain that nitrogen, potassium and phosphorous, for example, passing through in a waste water stream will be taken up by the water hyacinth plant. Each of these components has a value of its own. Combined into one fertiliser substitute in the effluent from an anaerobic digester they may have a significant commercial value.

1.4.4 Peat substitute

Peat is employed in horticulture as a medium for improving the quality of soils and is likely to become in increasingly short supply. The possibility of developing the use of water hyacinth as a peat substitute, rather as coconut fibre has been developed, is an area that requires further investigation. Such a peat substitute may be obtained as a byproduct from other water hyacinth processing.

1.4.5 Protein

The use of water hyacinth as a source of protein has received scant attention. There are, however, problems in the production of leaf protein and any system which is employed to extract the protein content from water hyacinth would have to be very carefully engineered.

1.4.6 Fodder

Water hyacinth has found application as a fodder for both cattle and pigs. There has also been an attempt made to process water hyacinth to a point where it can be fed to chickens. Whilst this may be a satisfactory short term solution to a lack of supply of feedstock it has been found that cattle fed with water hyacinth suffer from problems of the rumen. Chicken are found to die. On its own water hyacinth is not a satisfactory or staple diet for livestock.

1.5 THE DEVELOPMENT OF A PROPOSITION

1.5.1 Why has water hyacinth not been exploited ?

Despite a considerable amount of scientific and commercial interest it remains the case that wide-scale use of water hyacinth has not occurred. A study of the literature reveals that much of the previous work has concentrated on the material qualities of the plant rather than its energy content. It is, however, in this energy aspect that the greatest opportunities probably lie.

With regard to energy, almost all of the previous work has been undertaken by scientists, in academic or public sector employ, rather than chemical engineers or commercial organisations. The reported attempts at direct transfer of laboratory experience to field practice have indicated high process costs and the need for considerable operating skills, generally not available for the small-scale uses envisaged.

The present small commercial uses of water hyacinth, for example in basket making, have little potential for expansion. In general, they have tended to depend upon specialised markets.

1.5.2 Why then research further into water hyacinth exploitation

As has been indicated above, the resource is of such large size that if it were exploited it would have a significant impact upon the communities in which it grows. Being aquatic, it uses surface area which is not in competition with other land crops and will not, therefore, displace other forms of agriculture. Work to date has tended to view various aspects of the resource in isolation. There are many possible process routes. Before economic evaluation can be undertaken, it is necessary to subject the overall process, from cultivation to end-user, to engineering analysis and optimisation.

Energy is likely to be the most valuable and enduring resource to be obtained from water hyacinth. However, some form of symbiotic production of energy, fibre and nutrients (NPK) is possible. This is especially the case if pre-digestion treatment of the feedstock includes separation into indigestible fibrous, and digestible non-fibrous parts. The latter will form the feed to the digester whilst the former will be processed for non-energy uses. This symbiotic approach to utilisation deserves detailed investigation. Water hyacinth is a distributed rural resource which is difficult to transport. However, its energy yield, in the form of biogas, is applicable in rural areas themselves. On a larger scale, it can be economically transported to urban areas.

There is a continuing and expanding demand for energy worldwide. Biogas has a greater versatility than most other forms of biomass fuel. It can be used directly by combustion or it can be converted into electricity, with by-product hot water. There is also the possibility of removing the carbon dioxide component and using purified methane as a vehicle fuel. The potential energy value of water hyacinth per hectare makes it an attractive energy crop provided processing costs can be kept low enough and the energy viably distributed.

1.5.3 Proposition

On the basis of preliminary investigations the following proposition was, therefore, developed:

"Water hyacinth is commercially exploitable on a large scale provided that energy, in the form of biogas, is one of the outputs".

The thesis examines this proposition.

1.6 STRUCTURE OF THE THESIS

The following chapter examines the various basic process routes and product combinations, confirming the key position of energy production. It compares different ways of converting water hyacinth to a fuel and shows the advantage of the biogas route over alternatives. Chapter three analyses the various digestion alternatives, examines in particular the potential application of new digester types and the relations between the different components of a biogas production system. 'Juicing' ie the separation of the liquid parts of the water hyacinth plant from the fibrous parts, is identified as the process route promising a minimum capital-to-output ratio. Subsequent chapters identify the need for experimental data to support good system design and describe the acquisition of some of that data by experimental work in Bangladesh and Thailand.

In chapter seven experimental data, process design and economics are combined to conclude that the prospects for large-scale commercial utilisation are good and to identify the most promising process route. Bangladesh and Thailand, two examples of countries developing in different directions, are used as a context from which to assess different scales of application.

Chapter 2

OPTIONS FOR EXTRACTING ENERGY FROM WATER HYACINTH

The current chapter assesses the case for the utilisation of water hyacinth, with particular emphasis upon high-grade energy production. The principle options available for converting biomass into an energy resource are reviewed and those that are not suitable are discounted. Anaerobic digestion is selected as a process worthy of further detailed analysis.

2.1 SCALE OF THE OPPORTUNITY

Prior to commencing a broad analysis of the various technologies that may be applied to the conversion of water hyacinth into a useful form of energy, a preliminary assessment of the scale of the opportunity will help position the relevance of the current thesis. To facilitate this objective, Bangladesh is taken as an example.

The potential in Bangladesh

Bangladesh is located at the mouth of the Ganges and the Brahmaputra rivers. It is, therefore, not surprising that it has one of the highest ratios of inland water area per capita of population. The current rural population density is also high, with around about twenty people per hectare. Ponds, tanks and ditches are an integral part of the settlement pattern. When a new homestead is built a platform of earth is raised above the normal flood water level and the domestic dwelling built on top. As a result, ponds and ditches are formed in abundance. Ponds are generally square in shape and used for the long term storage of water for household use. Ditches are less deep and dry up during the dry season. It was observed during a limited random survey of rural Bangladesh near to Dhaka that for 871 homes there were 1794 ponds with an average surface area of approximately 300 m^2 (Sahm, 1984). Of inland areas, excluding paddy fields, under water for more than six months of the year, 10% (136,000 ha) is ponds and tanks (Bachmann, 1985).

A broad indication of the energy fixation potential by water hyacinth may be obtained from the following deduction: assume one tenth of all available ponds and tanks are used for water hyacinth harvesting; assume 200 dry tonnes/ha/year solids production; assume 450 m^3 of biogas per tonne with 20.4 MJ LCV per m^3; this equates to 25 PJ/year or 792 MW of continuous power. Converted at 30% efficiency to electricity will give 7.5 PJ/yr (237 MW). The production of electricity in Bangladesh in 1985-86 was put at 17.3 PJ (548 MW), with final end-user consumption being 11.9 PJ (377 MW) (BBS, 1987). On the basis of the conservative assumptions made above, it can be seen that water hyacinth may contribute up to 63% of the end-use electricity and 43% of the total production. The difference between production and end-use is put down to transmission losses and "own" use. In actual fact a considerable amount of electricity is stolen from the grid by illegal connection (Mahmud, 1988).

In terms of the rural economy, in 1985-86 it was reported that traditional fuels, ie. cow dung, rice straw, twigs and leaves, etc., supplied 9.3 million tons of coal equivalent (270 PJ). Water hyacinth production, with a 1% use of inland waters, could, therefore, contribute about 9% of this total but in a premium, gaseous form.

Scale of the opportunity on a global basis

Extending this rationale to a global assessment can only be made in simple terms. Bangladesh, with its unique location in the deltaic region of two large rivers, demonstrates the fact that every country is different. In Thailand, for example, large scale water hyacinth use will, in all probability, require man-made water surfaces. Without a considerable and extended analysis of each individual country in which the plant occurs it would not be possible to derive an accurate figure for the scale of the global opportunity. As a preliminary estimate it may be considered that there are some forty countries in which water hyacinth appears (Haider,1985). If on average each country were able to produce one half of the potential of Bangladesh the global energy contribution from water hyacinth would be 500 PJ (15.8 GW) thermal energy. The largest scale of use considered in chapter seven of this thesis will have a production capacity of 243 MW. To achieve the global production figure suggested it would be necessary to build sixty-five of the largest scale plants in forty countries each with a growing area of approximately 4.5 square kilometres. For the purposes of the current requirement, it is not unreasonable to conclude that the realistically achievable global energy potential from water hyacinth is between 475 and 630 PJ (15 and 20 GW) in the form of gas. This is equivalent to 0.2% of the 1988 global energy requirement.

The above generalisations do not provide any input from constricting factors, such as capital costs and revenue. The social and logistical problems associated with large scale utilisation are also not addressed. Were it possible to develop systems that could facilitate ready transformation of water hyacinth into methane and carbon dioxide the above estimate of potential may turn out to be a vast underestimate. The scaling of some of the fundamental determinants within the equation is covered by the subject matter of this thesis.

2.2 ENERGY FROM BIOMASS IN GENERAL

Prior to addressing the various techniques that may be applied to energy conversion with a water hyacinth feedstock, the various options available, and in use with other feedstocks, are discussed below under the heading of the physical state of the process output.

2.2.1 Solids

The use of wood and cow dung for combustion dominates energy utilisation in many developing countries. In Bangladesh, for example, traditional fuels include cow dung, jute stick, rice straw, rice hulls, bagasse (the residue from the production of sugar cane), twigs, leaves and various other non-defined wastes. In the year 1985-86 the commercial energy sector consumed 4,865,000 tonnes of coal equivalent energy (141 PJ) in the form of gas, electricity and coal. Energy supplied by traditional fuels accounted for 9,289,000 tonnes of coal equivalent (267 PJ) (BBS, 1987). This vast dominance of the energy sector by traditional fuels is only limited by the availability of the raw material. The predominant fuel from traditional sources in Bangladesh was rice hulls, with 2,177,000 tonnes of coal equivalent (63 PJ) contributed from this source alone. This was followed by cow dung which contributed 1,669,000 tonnes of coal equivalent (48 PJ) and then twigs and leaves with 1,343,000 tonnes of coal equivalent (38 PJ). The contribution from cow dung can be seen to be historically declining, whereas that from rice hulls and twigs and leaves is increasing. The problem with cow dung combustion is that it forms an acrid smoke which can seriously affect the health of those living in the environment of fires based on this fuel source. In Dhaka it is not uncommon to find whole neighbourhoods immersed in an acrid smoke, whilst at the same time families are carrying on their daily existence. In terms of energy content, twigs and leaves have a calorific value of 15.7 MJ/kg. This compares with cow dung which has a calorific value of 8.9 MJ/kg and rice hulls which have a calorific value of 13 MJ/kg. Coal on the other hand, will have a calorific value varying between approximately 20 MJ/kg and 30 MJ/kg, dependant upon the coal quality.

Two major problems encountered with the majority of biomass solid fuels are the comparatively low energy densities and the low calorific values that are attained. When compared with coal, for example, it is often necessary to handle two or three times the mass in order to have the same energy availability. This situation is made worse by the volume of biomass fuels. Certain air dried fuels, such as straw, will require to be severely compacted prior to producing a realistic source of fuel for general consumption. Air-dried straw has an energy density of around 2 MJ/m^3. Briquetting is a method of compressing and compacting such low density fuels in order to increase their utility.

Moving to the commercial production of solid biomass fuels, charcoal forms one of the major outputs from the pyrolysis of organic solids. (Discussed in greater detail in section 2.3.3 below.) Typically charcoal will yield 30% of the dry feedstock, on a dry weight basis, with a calorific value of approximately 30 MJ/kg. In order to produce charcoal of this quality, it is necessary to operate the pyrolysis process up to about 700°C. Charcoal from the gasification process (also discussed below), on the other hand, will typically have a calorific value close to that of pure carbon, which is 32.8 MJ/kg. With gasification the output of charcoal rarely exceeds 25% of the original dry feedstock mass. The energy content of charcoal is attractive when set against other biomass solid fuels but the cost of obtaining these fuels is high.

2.2.2 Liquids

The production of ethanol from the fermentation of alcohols is one which is contributing significantly to the energy requirements of several communities around the world. The requirement for petroleum substitutes, such as ethanol, is very much related to the price of oil on the world market. Following the 300% rise in fuel prices in 1973 there was a dramatic increase in the interest shown towards ethanol. The subsequent collapse of the OPEC cartel and its consequent depressive effect on world oil prices has resulted in a reduced interest in ethanol as a petroleum substitute. The conversion efficiency of sugar rich material, such as sugar beet and fruit, is in the range of 30-50%, with ethanol having an energy density of 28 GJ/m^3 compared to petrol at 32 GJ/m^3. This means that it can be used in existing vehicles without any need to convert the fuel storage space.

Another method of producing liquid biomass fuels is pyrolysis; heating the feedstock to an elevated temperature in a controlled oxygen environment. One of the products of pyrolysis is oil. The organic liquid which results from the temperature of approximately 700°C will have a calorific value of approximately 20 MJ/kg with the organic distillate representing about 25% of the dry feedstock. The problem with oil from pyrolysis is that it tends to be a heterogeneous mix of a range of different organics, and has limited direct application other than combustion as a low quality fuel.

As a further option, to operate downstream of a gasifier, methanol can be formed from low to medium energy gases produced by the gasification process. This is achieved by combining hydrogen with carbon monoxide. The reaction is exothermic and is encouraged by high pressures, although large scale industrial processes have been developed operating under various conditions of lower pressures and involving a reaction catalyst. Methanol is, again, an attractive petroleum substitute and its use may become widespread. The process of methanol formation is still relatively complex and inefficient and considerable development work is required to make this fuel a realistic option for a biomass utilisation project.

2.2.3 Gases

Municipal sewage sludge will produce approximately 430 litres of gas per kilogramme of dry solids, with a methane content of 78% in the gas, when anaerobically digested at 30°C. This represents a calorific value of approximately 27 MJ/m^3. The balance of the gas will mostly be carbon dioxide which can be readily removed with various technologies such as water scrubbing and pressure-swing-absorption using zeolites.

Other organic feedstocks, when anaerobically digested, will produce gas yields of varying quantities. Dairy waste sludge, for example, will produce 980 litres/kg dry solids when digested at 30°C, containing 75% methane. Grass can produce 500 litres/kg of dry solids with a methane percentage of 84% (Loll, 1976). Gas from such digesters can be employed directly for combustion, it can be utilised quite readily in internal combustion engines for the production of electricity, and it has, on occasion, been used as a vehicle fuel. One of the problems with methane, in general, as a vehicle fuel is that it is not possible to convert it into a liquid by pressurising alone and its energy density is, therefore, low in comparison to other liquid fuels. It is possible to convert methane into a liquid by reducing its temperature to -180°C but this is rather an impractical method for the large scale use of this gas as a fuel, for example for transportation, other than within the context of the worldwide liquid natural gas market. It is not possible to provide absolute insulation against heat inflow to cryogenic liquids. The result is that there is a certain amount of loss as the period of storage prior to use is extended.

Low energy gases produced by gasification have a calorific value of around 10 MJ/m^3. The gases typically produced by this process, where air or oxygen is introduced into the combustion chamber, consist of carbon monoxide, hydrogen, carbon dioxide, methane, water and nitrogen. In the case of pyrolysis where air is kept out of the process, the gas will typically be to the order of 15 MJ/m^3 and will represent approximately 20% of the dry solids feedstock. With low energy gases the immediate benefit can be obtained by use on site for heat generation such as required in steam raising plant. The possibility of using this gas in other applications is one which has limited potential.

2.2.4 Biomass fuels in general

There are a number of factors which affect the use of biomass fuels and these may be summarised as follows:

- they are, in general, not in a form immediately suitable for energy use
- they may only be available at a distance from the site of use
- they can be physically difficult to handle
- it is often the case that they are unpleasant to handle and in some circumstances may be toxic
- they may contain a very high water content

There are three fundamental approaches to the use of biomass for the production of fuels. These are: direct combustion, dry chemical processing and aqueous processing. The question of the water content of biomass feedstocks is one which plays a significant part in dictating which routes can be chosen. Even freshly harvested timber usually contains around 50% water. For direct combustion to occur the maximum possible water content is typically around 15%. To remove moisture from 50% down to 15% requires approximately 20-25% of the calorific value of the dried wood itself. For each kilogram of water removed 3.5-4.5 MJ of heat is required. At the extreme, with the water content above 80%, less than 5% of the dried biomass' original energy content would remain after subtracting the energy consumed in evaporation (Dept.of Energy, 1976). Where the possibility of reliable sun drying is not available biomass feeds with a high moisture content may, therefore, be excluded from the direct combustion and the dry chemical processing route options.

Whilst the potential for the use of biomass as a source of fuel is clear, there remains a significant development requirement. A number of technical difficulties remain to be solved with both biochemical and thermochemical processing systems and until these have been successfully dealt with the large scale application of biomass as a fuel feedstock is likely to remain limited for use in special circumstances.

2.3 ENERGY UTILISATION POSSIBILITIES FOR WATER HYACINTH

There are several techniques available for the conversion of water hyacinth into a useful form of energy. The suitability of each depends upon the form in which the feedstock is available. As part of the development of a methodology for using water hyacinth, possible techniques will be discussed at this point in the thesis and discounted from further consideration if they are unsuitable.

2.3.1 Direct-burn/ briquetting

Sun drying and then direct burning is currently used on a small scale in certain parts of the world. With a moisture content of 10% the calorific value of dried water hyacinth is 7.7 MJ/kg (Philipp, 1983). Reducing the moisture content to this level requires high ambient temperatures and low relative humidities. Clearly, during any monsoon season production would have to cease. At a 10% moisture content the air dried energy density is 1.3 GJ/m3, which compares very unfavourably to bituminous coal, with an energy density of 19.2 GJ/m3, and wood, with an energy density of 9.8 GJ/m3. The problem with larger scale applications is that the amount of handling required will be very restrictive; the major portion of the fresh weight is water. It will be necessary to have a large area for sun drying and the plant matter will need to be double handled. Only if the moisture content can be reduced with relative ease to around 10 to 15% would this be an option of much interest.

An alternative approach to the question of using water hyacinth has been to dry the plant material and compact it in briquettes for burning as a coal or wood substitute. Once again this appears to be a very attractive option for gaining some benefit from the high rates of plant matter production that are available. The resulting material has an energy density of 8.3 GJ/m3, which is comparable to charcoal at 9.6 GJ/m3. The capital investment required to establish a briquetting operation is composed of the machinery to disintegrate the dried water hyacinth, screen and chop it to 6mm particle size and then compress it into briquettes or pellets. There is also the value of the land upon which sun drying will take place. For a plant to produce 40 tonnes/day of briquettes, during a monsoon climate dry season, an area of 12 hectares will be required. The harvest would need to be 1,300 wet tonnes per day. In reality however, as with direct-burn, the drying of water hyacinth to a satisfactory level is an area of major difficulty. The sun must also be shining with an intensity that will ensure the plant is thoroughly dried. High humidity levels will reduce the speed at which the plant dries and consequently increase the area of land required. To ensure satisfactory reduction of the moisture content to a level where briquetting may realistically be accomplished it is necessary to utilise energy inputs other than solar energy. This generally will require the use of energy produced by the process itself in order to commence with a satisfactory feedstock. Research to date suggests the amount of energy produced in the form of briquettes is inadequate to dry the water hyacinth. This being the case, the overall system efficiency would be negative (Koser, 1982).

2.3.2 Gasification/ pyrolysis/ carbonisation.

These three process are all involved in the low-temperature carbonisation of biomass. With aquatic plants as a feedstock the collection of the distilled liquid products would not appear to be viable. Separation of this pyroligneous mixture into useful constituents, such as acetic acid, methanol, ketones, phenols, etc., requires complex chemical processing plant. The main product from the carbonisation process is charcoal. The gas produced as a by-product could be used to increase the overall energy efficiency of the process.

In case of carbonization the dry matter within water hyacinth is heated to a point where it is converted into carbon. This carbon is used for subsequent combustion to form heat. In the case of pyrolysis the water hyacinth's solid content is again heated, but this time to higher temperatures than in the case of carbonisation, with the result that oils as well as char are produced. The oils can then be used for combustion as a liquid fuel. Water hyacinth has been studied for use in both of these processes and, as with briquetting above, the major problem is the removal of the high water content prior to introduction into the formation process. The only realistic way in which such high volumes of water may be removed from the water hyacinth is by sun drying. This, almost by definition, means that it can be employed at very specific locations where there is a low relative humidity and a large area of land available. Such is the case in the Sudan where the River Nile runs through the deserts of the Sudan and Egypt. The collection of water hyacinth and its deposition in tracks of arid ground is a realistic possibility. Work carried out by Philipp in the late 1970's would, however, suggest the overall energy economics of the process are not attractive.

Apart from the problem of reducing the moisture content, a further problem with water hyacinth is that the ash content will need to be reduced if a useful fuel is to result. The ash content of air dried water hyacinth has been put at around 40% (Philipp, 1983). Other researchers have placed it in the region of 15-30% (See Tables 4.1 and 4.2 in Chapter 4). Overall, the capital investment and the technical sophistication required make the carbonisation route appear to be rather unlikely.

2.3.3 Hydrolysis/ fermentation

This process route results in the production of liquid fuels, the principal one of which is ethanol. The hydrolysis/ fermentation route is particularly suitable for use with feedstocks having a high moisture content and aquatic weeds may, therefore, at first glance, be considered suitable for conversion to ethanol.

Cellulose and hemi-cellulose polymers constitute, in approximately equal amounts, 50% by weight of the dry solids content of water hyacinth (Pillai, 1983). Not all the constituent sugars are,. however, hexose molecules. Hemi-cellulose polymers may contain substantial amounts of pentose. Pentose molecules cannot be fermented to ethanol by the yeast strain (*Saccharomyces cerevisiae*) employed for ethanol production. A general pre-requisite to the production of ethanol is that there should be available a yeast-fermentable glucose substrate. To obtain this it is necessary to apply differing degrees and methods of pre-treatment and it is at this stage that the problem arises for aquatic weeds. Only in a few species of plant, such as sugar cane and sugar beet, is the extraction of simple sugars commercially viable. The hydrolysis of cellulose requires comparatively high temperatures, strong acids and pressurised reactors. Enzymatic hydrolysis, which is an alternative to chemical hydrolysis, is also difficult with cellulose because pre-treatment is required to free the associated lignin before enzymatic hydrolysis can take place. Cellulose hydrolysis is, in fact, not practised commercially in the free market economies because previously developed technologies, such as the Scholler and Madison processes are considered to be uneconomic (Reed, 1980).

With respect to aquatic weeds, very little work has been done on this subject. It has been suggested that a total hydrolysis with sulphuric acid in a two stage process, at 120oC and then 185oC, may result in approximately 20% dry weight glucose and 9-10% xylose using fresh water hyacinth with 15% water (Philipp, 1983). However, the energy balance indicates an input to the process of ten times the energy made available as a liquid fuel (Slesser, 1979). Ethanol production would, therefore, only be considered in very specialised circumstances, where liquid fuels were required at the expense of other sources of energy.

2.3.4 Anaerobic digestion: the current process under review for water hyacinth

Being a wet process anaerobic digestion is particularly well suited for the conversion of aquatic plants into biogas. As a by-product, the process will also produce a slurry that may be useful as a fertiliser, having high concentrations of N,P and K. It is the contention here that any viable utilisation scheme will require the use of all parts of the plant. Optimising the balance between two or three outputs will, therefore, be of senior importance to simply maximising gas output.

The main cost of an anaerobic processing system is that of the digester itself, and, if necessary, a gas holder. Storage of biogas, for more than a few hours, is generally considered prohibitively expensive since gasometers can cost four times the digester itself (Boyles, 1984). The gas must, therefore, either be used or disposed of immediately. Current practice in developing countries is to use digesters with residence times to the order of 30 days, often incorporating a floating cover to provide a certain amount of gas storage capacity. If one is contemplating, for example, the construction of a system to produce enough gas to generate 20 kW of electricity on a continuous basis, using a spark ignition internal combustion engine, the daily harvest of water hyacinth will need to be 10 tonnes. With a 30 day retention time and a solids concentration of 2% the digester will need to have a volume of 750 cubic metres. This may present great problems, especially when it is remembered that the digester must be sealed to prevent the ingress of air and the egress of gas. It is for this reason that attention has turned to the possibility of employing high-rate digestion techniques.

Whilst one of the principle subjects of the current research programme, the possibility of converting water hyacinth to biogas has been an area of major interest for many years. The factors which offer attraction for using this route are well understood by researchers in this field. The problems are equally well understood. The high water content of water hyacinth means that harvesting effort receives a low reward in terms of organic matter available for conversion by anaerobic bacteria into biogas. This increases transport costs. Once the water hyacinth is introduced into anaerobic digesters the high porosity of the plant, with a significant percentage of air trapped within its fabric, ensures that the plant floats within the anaerobic digester. After a period of time, during which the plant decomposes and the oxygen is released or consumed by aerobic bacteria, the water hyacinth material will sink to the base of the digester and then be converted into a mass of matted stems, blocking the successful operation of any further processing. The lignin within the plant is resistant to attack by anaerobic bacteria (a quality often referred to as "refractory") and will gradually build up to a level which requires removal. Biogas production from water hyacinth, whilst the subject of many research efforts, has still to be implemented on a realistic commercial basis.

The current thesis is based upon the premise that the use of water hyacinth will only be viable with anaerobic digestion. This must further be qualified by requiring that high-rate digestion techniques must also be employed in order to obviate the requirement for large reactor vessels.

Chapter 3

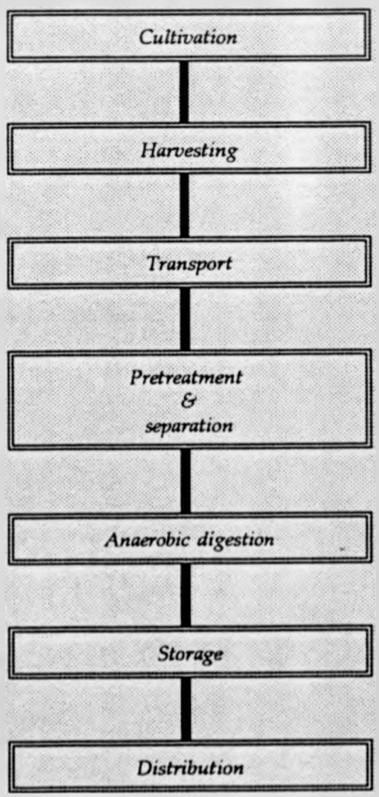
THE BIOGAS PRODUCTION SYSTEM - UNIT PROCESSES

The current chapter will provide a first level of analysis of the system proposed for water hyacinth utilisation. This covers the principle components in a potential system and ends with a assessment of the product forms.

3.1 SYSTEM OVERVIEW AND BLOCK DIAGRAM

Prior to studying the complete system it will be useful to summarise the various stages in order to define the overall context.(Figure 3.1)

Figure 3.1 Water hyacinth utilisation - process flow sheet.



Cultivation

One of the primary considerations in the process under review is whether to use water hyacinth in the wild or in cultivated growth ponds. There are many apparent social benefits to be gained from collecting from the wild. The concept of removal of the clogging weed from rivers and canals has numerous attractions. However, set against this vision must be placed economic factors, such as the cost of transporting the harvested plant from open waterways to a point of utilisation. Another advantage of harvesting wild plants is that nutrient addition to enhance growth is not required. Water hyacinth grows luxuriantly on open waterways in certain parts of the world as a result of the high levels of nitrogen and phosphorous that are to be found. Set against these benefits is the consideration that the rate of growth and harvesting could be more carefully controlled were growth managed in growth ponds. This is a subject which will be discussed in greater detail later in this chapter.

Harvesting

Once the water hyacinth plant has reached maturity, with regard to its optimum for utilisation, it must be removed from the water and transported to the point of use. Harvesting is an area that has been the subject of considerable research and analysis. As mentioned in Chapter 1, the US Corps of Engineers has developed many forms of water hyacinth harvester to keep open public waterways in the United States. This work forms the basis for techniques with which to harvest water hyacinth. The question of the location of growth will affect the choice of the method of harvesting. Harvesting within growth ponds will be less complex as the plant can be encouraged to grow in one direction and may be harvested from one point. Growth in the wild will require the harvester to be mobile, travelling the waterway and returning with harvested water hyacinth to the point of use.

Transport

One of the major problems with water hyacinth is that the whole plant has a water content of approximately 95%. Transport costs for moving the water entrained within the plant are, therefore, high. It will be a primary objective of a viable system to minimise transport costs. The method of transporting water hyacinth from the point of harvest to the point of use may be in various forms. It has been suggested, for example, that the water hyacinth may be slurried immediately it is harvested and then pumped with slurry pumps to the point of use. (Lecuyer, 1976) Alternatively, a conveyor belt of some sort will be required to move the plant mass to the point of use.

Pre-treatment and separation

As has been amply demonstrated during the course of numerous experiments, water hyacinth will require some form of pre-treatment (Jogelakar, 1984 & 1985; Eusuf, 1988; Hannan, 1990). The harvested plant, with the exception of the leaf portion, is not amenable to anaerobic digestion without some modification to its structure. The root portion, for example, has been demonstrated to be resistant to anaerobic bacterial attack, and requires to be broken down in order to accelerate the process of digestion (Pillai, 1983). At this point in the system, it is also necessary to consider the possibility for separating out other useful fractions of the plant. In a juicing process, to be discussed more fully in the ensuing text, lignin may usefully be removed with a press after the plant has been slurried. The lignin fraction of the plant will not be reduced by attack by anaerobic bacteria. Lignin on the other hand has value has a fibre and its removal at the pre-treatment stage would effectively increase the overall value of the process.

Anaerobic digestion

The vagaries of the anaerobic digestion of water hyacinth, or for that matter any source of biomass, to produce methane and carbon dioxide, has been the primary cause of system failures (Eusuf,1988; McMullan,1977). Anaerobic digestion is a complex subject and one that has been receiving detailed attention in only comparatively recent times. As understanding of anaerobic digestion increases, it has become apparent that it is not a simple process that can be carried out in the same manner as ploughing a field. It requires an understanding, for example, of the importance of pH within the overall process. Monitoring the pH is an integral part of running a successful anaerobic digester. A further major drawback that has to date been an obstacle to the effective wide scale use of anaerobic digestion has been the problem of retention time. The longer the retention time, the larger the anaerobic digester needs to be to produce an equivalent volume of gas. Typically the Indian style of anaerobic digester requires a retention time of between forty and sixty days, whereas recently developed high-rate anaerobic digestion processes have a retention time to the order of twenty-four hours; soluble organic waste streams can achieve up to 95% reduction in COD within this period (Grobicki,1989). The anaerobic digestion of water hyacinth has proved to be a sticking point for many researchers looking at using water hyacinth as an energy resource (Pillai, 1983). It is for this reason that the current thesis places great emphasis on the time factor and high-rate anaerobic digestion is seen as a primary requirement for the successful utilisation of this aquatic plant.

Products

The requirement for storage and distribution facilities will depend upon the products produced and the markets for which they are intended. A brief summary of the potential products is given below.

Gas Anaerobic digestion produces biogas with a typical methane concentration of approximately 55-60%, the balance being carbon dioxide. Both of these gases have commercial value. Methane may be used as a source of energy for transportation, for raising heat in all forms of industrial process or for generating electricity. Carbon dioxide has a value as an industrial gas in food processing industries, as well as in other associated light and heavy industries. The question of the best method of using the gas is one to which we will return.

Fertiliser It has been reported from India that in many cases the effluent from an anaerobic digester has been found to have more value as a fertiliser than gas produced by the anaerobic digestion process. This may be expected with long retention time digesters where the fertiliser may be sold but the biogas produced has only limited value as a collected fuel-wood substitute and for local domestic lighting. Gas production from the Khadi Village Industries anaerobic digester, for example, is relatively low in terms of gas per cubic metre of anaerobic digester per day. The anaerobic digestion of water hyacinth results in a very low solids, high nitrogen content liquid, and its use as a liquid fertiliser is one that will receive further attention in this thesis.

Protein The possibility of using water hyacinth as a source of protein is one that is currently in receipt of research attention. (Gooding,1991) It would appear that this may be an additional source of income generation, or added benefit, for the system proposed.

Fibre As has been mentioned above, the separation of water hyacinth into soluble organic fractions and lignin/cellulose is one which will result in a high fibre content residue. Fibre is a substance which has a value of its own and it is anticipated that the affective removal of fibre from the water hyacinth plant prior to digestion will provide yet another by-product with its own value.

Overview

The system proposed from cultivation to utilisation is one that has resulted from the analysis of research efforts to date. It is not claimed to be a new appreciation of the opportunity. The objective here is to clearly identify those bottlenecks which have prevented large scale and realistic utilisation of this immense resource and, by a process of analysis and deduction coupled with limited experimentation, to devise methods of overcoming these obstacles.

3.2 THE SYSTEM IN GREATER DETAIL

3.2.1 Growth of feedstock / cultivation of water hyacinth

Wild plants - rooted/floating

Wild plants appear in many diverse forms. As referred to in Chapter 1, the water hyacinth may be found to be rooted to the base of its habitat, with the roots penetrating the muddy bottom of ponds and lakes, or floating freely. The plant adapts to its growth environment. Initially when the number of plants is small, it will grow horizontally spreading its leaves and minimising stem growth. As the growth proceeds, the plant will produce large stems with foliage appearing at different heights in its growth. This uncontrolled development of the plant in the wild is one which will not allow potential users of water hyacinth to control the plant growth in an optimum manner. For example, it has been clearly demonstrated that the water hyacinth leaf is the most suitable for anaerobic digestion and fertiliser production. It is low in lignin and high in soluble organics. The COD of leaf, for example, is typically 130,000 mg/m^3. On the other hand, the stem is high in lignin with a correspondingly lower COD, typically 57,000 mg/m^3.(See sect 5.3.2) The stem has been found to contribute approximately 50% by weight, both wet and dry, of wild plants. Where the objective is to maximise fibre production, it would be desirable to encourage stem growth. This will be achieved by maintaining high plant density. Where fibre production is not required minimal stem growth would be achieved by minimising plant density. As a point of observation, it has been noted by the author that in both Bangladesh and Thailand plant densities are commonly such that the production of long stems is a common attribute in wild plants. Indeed it would be difficult to maintain a system that did not produce long stems. In the wild it is common to find that plants are actually floating and not rooted to the base of the water medium. Therefore, as a general case, the growth of wild plants leads to high fibre production and generally diluted digestible organic production.

Cultivated plants

As has been described in the above paragraph, by cultivating the water hyacinth plant, it is possible to optimise the type of production required. In a system which is aimed primarily at producing biogas, it would be desirable to maximise leaf production and minimise stem production. A further advantage to be gained from cultivating plants is that the growth rate may be significantly accelerated by the passage of other dilute organic waste streams through the growth ponds. Studies carried out on the growth rate of water hyacinth located on ponds receiving effluent from the secondary treatment of sewage sludge demonstrate conclusively that the growth rate may be doubled over that of wild plant (Wooten, 1976).

Growth rate factors

The growth of the water hyacinth plant can be affected dramatically by various environmental factors (see para.1.3.3) For example, water hyacinth will not grow in salty water. Where the chloride ion reaches the level of sea water, the plant growth will be terminated very rapidly and the plant will die. Also, if the temperature drops below approximately 20°C growth will cease (Penfound, 1948). Where the requirement for the absence of chloride ions is met and the ambient temperature is typically in the region of 30°C, the predominant factor affecting growth then becomes relative humidity. Work carried out in the Sudan has demonstrated that, in certain circumstances, relative humidity will affect plant growth more significantly than temperature (Philipp,1983).

The question of influencing nutrient uptake to optimise plant growth is one which has likewise received considerable attention. It has been amply demonstrated that various nutrients will accelerate the growth rate of the plant significantly. The presence of potassium, nitrogen and calcium, for example, in the growth medium has been demonstrated to have a considerable effect (Singh, 1983). It would appear from the available literature that the relative strength of amoniacle nitrogen and nitrates in the growth medium is not one which has a concentration-limiting effect on the growth of the plant. Higher concentrations of these two forms of nitrogen have been demonstrated to result in dramatically increased growth rates (Wooten, 1976).

Seasonal factors

As has been mentioned above, when the temperature drops below 20°C the growth of water hyacinth will cease. In certain parts of the world the variation in seasons results in significant fluctuations in temperature. In Bangladesh and Thailand, however, the two countries studied with regard to the utilisation of water hyacinth in this thesis, the temperature very rarely drops below 30°C in the low lying regions. In Thailand the minimum temperature is typically 27-28°C in the cold season and 40-42°C in the hot season. A similar range of temperatures is found in Dhaka in Bangladesh. For this reason the seasonal effect of temperature on the growth of water hyacinth is not a limiting factor in these two countries. In Bangladesh one seasonal effect that is a severe limiting factor on the availability of water hyacinth is the annual flooding. It has been observed by researchers that when the floods come the plant is often washed away. During several visits to Bangladesh in the course of this study, it was noted during periods of flooding that the growth of water hyacinth accelerated. Because of the flood factor it would be very difficult to maintain control of a cultivated crop, especially if the floods entered into the area of growth. As a wild plant, however, the opportunities for collection are dramatically increased by flooding. The water hyacinth plant was found to invade every available nook and cranny of flooded territory. (See Plate No.4) The flood waters are often high in nutrients having been produced by water washing soil from the foothills of the Himalayas. Seasonal growth is a very important factor in evaluating the opportunity for utilising water hyacinth. In the southern United States, work carried out by various researchers indicates that seasonal growth may vary enormously and in certain periods of the year growth ceases completely (Penfound, 1947; Wolverton,1979). Clearly, should this be the case, the operation of the processing plant will likewise cease. In a properly designed system, this in itself need not be a limiting factor, but it is an aspect of a viable economic project that must be taken into account.

Introduced biological vectors

A conclusion that can be drawn from the system overview it is that there are several key stages in the utilisation of water hyacinth that will affect the overall economic performance of any utilisation scheme. As has been alluded to in the foregoing paragraphs, there are a number of key elements to the selected pattern of growth that will have a significant effect. Growth rates of selected portions of the plant need to be established and controlled. Amongst factors out of the control of operators that may affect growth rate is the proposal by various governmental authorities, concerned by the damage resulting from water hyacinth, to introduce biological vectors that will attack the plant. This is a matter for concern. The debate with regard to whether or not such vectors should be introduced has been ongoing for many decades. The first mention of this topic was in the early 1920's (Buckman, 1920). Subsequently, it has been repeatedly brought up throughout the course of this century until the present day. The fact that by the end of the century there is still no appreciable utilisation of water hyacinth would indicate that in the wider scenario the most economic way forward would have been to find, as rapidly as possible, a method for destroying the plant.

The contention made here is that the introduction of biological vectors is not of necessity a threat to the harvesting of water hyacinth as an economic crop. It is quite normal in farming to raise crops where the possibility of biological attack of some form or another is a real threat.

The situation with water hyacinth, if agents for its destruction were successfully introduced, would be significantly less complex. In the case of wheat, for example, there are numerous sources of potential attack. If there were one clearly defined biological agent which could attack and destroy water hyacinth this would be readily dealt with, by comparison to the case of wheat. By isolating the agent and treating the harvest in such a way that it was not effective in its attack on the harvested crop, damage potential could be mitigated. Set against this view, of course, would be the cost of controlling such attacks. This would need to be considered along with the cost of fertilising the crop to ensure maximum growth is obtained. Work carried out by researchers in the area of biological control suggests that introduced vectors will be typically of one generation. They would be released in specific locations and would be clearly identifiable. It is an important part of any programme for the introduction of biological pests to ensure that the introduced vector will not run rampant and destroy crops that are intended for use as food.

Table 3.1 *Growth rate of water hyacinth.*

Growth	Wolverton 1976	Boyd 1970	Yount 1970	Westlake 1963	Dymond 1948	Penfound 1956
$g/m^2/d$ (dry wt)	73	14.6	40	7.4 - 22	34.6 - 54.5	12.7 - 14.6
t/ha/yr (dry wt) *	154	54.7	146	27 - 80	126 - 199	46 - 53
Standing crop kg/m^2	22	-	-	1.5	-	-

* *calculated over 365 days unless specifically stated by reference author*

Growth facts

In 1970 research carried out in Florida on milorganite and hydrated lime fertilised ponds recorded daily net productivities of greater than 54 g/m^2 on a dry weight basis.(Table 3.1) In this study (Yount and Crossman, 1970) the average daily values were in the region of 40 g/m^2. Westlake (Westlake, 1963), calculated a seasonal maximum biomass of 29 kg/m^2 fresh weight and 1.5 kg/m^2 dry weight in the same area of the United States. His figures indicated a daily productivity of between 7.4 and 22 g/m^2 dry weight and an average biomass of 1.473 kg/m^2 dry weight. Dymond (Dymond, 1948) estimated a yield of between 34.6 and 54.5 g/m^2 per day on a dry weight basis. Penfound (Penfound, 1956) reported daily productivity of water hyacinth in Louisiana to be

12.7 to 14.6 g/m^2 dry weight. Boyd (Boyd, 1970) listed theoretical maximum rates of production, based on Penfound's data, of 12.8 metric tonnes per hectare and a maximum daily production of 14.6 g/m^2 dry weight and a maximum annual yield based on daily productivity rates of 54.7 metric tonnes per hectare, or 5.47 kg/m^2. As is clear from the foregoing data, the growth rate, or rather, its appreciation, can vary enormously. It has been demonstrated that even high rates of production can be doubled by the introduction of a nutrient feed into the growth pond, such as from a sewage farm or some other organic waste stream. (Wooten, 1976) Alternatively, one hectare has been estimated to be able to yield 215 tonnes dry weight per annum in the Southern States of the USA over a growing season of seven months (Wolverton, 1976).

3.2.2 Harvesting/collection

Methods of Harvesting

The variety in methods of harvesting is enormous. In Sudan harvesting was carried out by manual workers wading into the edges of rivers and manually dragging mats of water hyacinth plant to the shore. (Philipp, 1983) This work demonstrated clearly that the amount of harvesting achievable per man per day can vary depending on the level of supervision employed. This latter factor is not one that would surprise many people. The work, carried as part of a German aid programme, indicated that productivity per man per day can fall to a third in unsupervised groups, typically ranging from 300 kg per man per day to over 1,000 kg per man per day. One of the principle problems with manual picking is that the plant produces some form of irritation in human skin. Its collection is not, therefore, a highly desired occupation. In Bangladesh it was discovered that premium rates were required for water hyacinth picking because of this problem. In 1987 a typical Bangladesh labourer would earn 75 pence per day, but for collecting water hyacinth it was necessary to pay over £1 per day. (There is a temptation to suspect that the higher rate may have resulted from the fact that the paymaster was a Western operator, but to determine this would have required investigation outwith of the current research effort.) Mechanical harvesting studies carried out in the southern United States have demonstrated that mechanical harvesting will ensure much high yields than manual harvesting, as one would expect. (Wolverton, 1979) The mechanical harvesters, employed in the studies referred to, were, in fact, idle for most of the time as the pond that they were required to harvest was too small to utilise their full capacity. Harvesting rates of 36.7 tonnes/hr were achieved by a shore based conveyor-harvester. This must be set against the cost of running, and the capital cost of purchasing, such a piece of equipment. A free floating, roaming mechanical harvester achieved a harvesting rate of 9.1

tonnes per hour. Such a piece of equipment would be an essential ingredient in a system which relied on the harvesting of wild plants. It may be that such a harvester would find that its costs are partly covered by the requirement to remove water hyacinth from public waterways. It is almost certain, however, that in Bangladesh such public funding would not be available to subsidise or assist in a programme of utilisation of water hyacinth.

The preferred option for harvesting would be to grow the plant in such a way that it was harvested from one point only and that moving the harvester from location to location was not required. This could be managed in growth ponds where the plant could be collected from one end of the pond on a daily basis and the growth pattern arranged in such a way that the vacant space was always filled with plants ready for harvesting. Proposals by Lecuyer (Lecuyer, 1976) involved constructing serpentine canals, each up to 40 km long, with a total canal length for the scheme of 26,240 km, providing the feedstock to a 5.66 million m^3/day pipeline quality gas producing project, equal to a power transfer of 2.29 GW. The intention was to either inject purified methane gas into a utility pipeline or sell it directly to a large industrial user. The proposal was that the arrangement of the canals would feed the plant to a central "fine hyacinth copper" where it would be harvested and slurried prior to transporting it back to the point of utilisation. The anaerobic digesters were an area of difficulty being based on a ten day retention time. The volume of sealed digester calculated as necessary was 22.4 million cubic metres. It is perhaps not surprising that it did not materialise. With an estimated capital cost of $596 million, a return on investment of 11.5% and a payback period of 9.8 years it was probably rather difficult to secure the necessary capitalisation for what would have been the first project of its kind. It is of interest to note, however, that this concept for large scale utilisation exists but that the method has yet to be refined to a point where it will make unambiguous commercial sense.

Methods of transport

Once the plant is harvested, it is necessary to move it from the point of harvest to the point of use. Once again, the immediately available means of accomplishing this objective, particularly in Bangladesh, is through manual labour. In Bangladesh this method of transport may not prove to be unrealistic. Manual labour is abundant, unskilled and, in terms of world energy prices, not expensive. It is a notable feature of developing countries, such as Thailand and Bangladesh, that first world facilities, such as telephones and electrical energy, are comparable in cost with those in the first world. Other, and substantial, portions of the society, however, are operating on the basis of third world prices. Into this category falls the cost of manual labour and of locally produced food. The use of manual labour for the transport of water hyacinth would, nevertheless, introduce a limitation to the size of the operation that may be established. In the light of the fact that the plant is 95% water, the primary objective is to minimise the distance requirement to transport the plant from the point of harvest to the point of use. In a full scale utilisation scheme the very nature of the resource would make it difficult to obviate the requirement for transport and it is probable that the method of transport from the point of harvest to the point of use would need to be mechanical, in some form of other, as opposed to human. No doubt this is a point to which human ingenuity can be applied. The harvested plant is sent on a one way trip. There are no return loads envisaged at present. However, it would clearly be advantageous if the effluent from the water hyacinth digester were used to feed the growth ponds, if cultivated growth is selected; in this way necessary nutrients would be continually recycled.

Transport costs versus energy content

The equation for calculating the cost of transport is elementary. This can be set against the level of energy productivity per unit of plant to determine the effect on the overall efficiency of the system. As has been alluded to above, the water content of the plant implies that minimum transport costs should be a primary objective. The possibility of using gravity to feed harvested plants to the point of use is one that should be seriously contemplated.

Typically one tonne of water hyacinth will have 5% solids content and 95% moisture content. The energy requirement for transport will depend upon the mode of selected. In the case of a slurry pump, the power requirement would be a function of the hydraulic gradient and the pressure drop in the pipeline. The power requirement to transfer one tonne of water over a distance of 1 km in one hour with a slurry pump may be taken as (say) 0.5 kW. (Pipe OD = 100 mm; flow rate = 0.278 l/sec) The energy content of one tonne of harvested plant, on the other hand, is based on the assumption that one tonne wet weight of water hyacinth will produce approximately 22.5 m^3 of biogas, (450 cubic metres per dry weight tonne) with a methane content of 60%. This in turn provides an energy content for one tonne of harvested plant of 472.5 MJ; transported over an hour this gives a power rating of 131.25kW.

As can be seen from the foregoing, the reduction in efficiency of the overall process by transporting one tonne of water hyacinth 1 kg across level ground will be about 0.4 %. This analysis does not take into account the value to be obtained from fertiliser, protein and fibre that is planned to be an integral part of the overall system.

Slurrying and pumping

With the system that is proposed in the current thesis, the feedstock will be slurried prior to the extraction of juice. There is a strong case for suggesting that the slurrying should take place at the point of harvest. In a purpose built system for growth, harvesting and transport to point of use, the slurried water hyacinth could then be transferred by means of a pipe network. The use of hydraulic head could be employed to maximum advantage to assist in the transfer, as is commonly the case in the distribution of water by means of water towers.

3.2.3 Pre-treatment

The need to pre-treat water hyacinth feedstock prior to digestion is an unavoidable consequence of requiring high-rate digestion. There are a number of options available.

Chemical pretreatment

<u>Principles</u> Chemical pre-treatment allows the structure of the water hyacinth plant to be modified significantly to make it more amenable for anaerobic digestion. The first stage in anaerobic digestion is solubilisation or hydrolysis. The hydrolytic bacteria have a significant task to perform in the case of water hyacinth, the structure of the plant is bound in and moulded by hemicellulose and lignin, both of which are difficult to hydrolyse. By means of chemical pre-treatment, it is possible to break down the structure of the hemicellulose and the lignin to a point where the hydrolytic bacteria may enter and perform their function at a far greater rate than would otherwise be the case.

<u>Acid pre-treatment</u> The use of a suitable acid, such as hydrochloric or sulphuric acid, which will not affect the overall efficiency of the process, has been considered by several research teams (Hillman, 1978). The acid would be employed in a very low strength concentration and the acid pre-treatment would be carried out fairly rapidly. The disadvantages of acid pre-treatment are the introduced cost of the process set against the benefit that may be achieved. Acids would need to be obtained from manufactured sources and for this reason they would have a cost inherent in their procurement.

<u>Alkali pre-treatment</u> Once again dilute concentrations of various alkaline substances may be used to pre-treat the plant, such as lime or caustic soda. The advantage over acid pre-treatment is that lime would generally be available locally and it would be possible to obtain it at a price which in all probability would not significantly affect the overall

process, or at least not to the same degree that acid pre-treatment would imply.

Reasons against chemical pre-treatment The possibility of chemical pre-treatment is one that should not be dismissed. It may be that in certain specialised circumstances, this is a real opportunity for improving the overall performance and economics of the system. Should a low cost supply of acids or alkalis be available, then serious consideration should be given to their use. However, in a majority of cases it is likely that the introduction of acids or alkalis will prove to be an unnecessary economic encumbrance. It is probable that other methods of pre-treatment would be more cost effective and will generate better results for the overall system. The chemical pre-treatment of water hyacinth will not break down the lignin or hemicellulose unless the chemicals are strong. This being the case the problems of blocking will not be alleviated.

Biological pretreatment

Principles As with chemical pre-treatment the objective of biological pre-treatment is to accelerate the hydrolytic phase of the anaerobic digestion process. By allowing a period of plant matter decomposition prior to introduction of the feedstock into the anaerobic digester it is possible that the overall process efficiency may be increased. It would be theoretically possible to introduce either anaerobic and aerobic bacteria into harvested water hyacinth in such a way that decomposition occurs. Such decomposition would not in itself be high-rate and it would be necessary to set aside quite a relatively large area for this effect to be successfully achieved.

Aerobic pre-treatment Aerobic bacteria that bring about the decomposition of organic matter are ubiquitous. Any plant material that is harvested and left in moist and warm conditions will be attacked by bacteria which will cause the readily degradable organic material to commence hydrolysation and decay. This is, in fact, the primary stage of both the aerobic and anaerobic reduction of plant matter.

Anaerobic pre-treatment As with aerobic pre-treatment, the bacteria which carry out the hydrolysis of the plant are ubiquitous. In the case of anaerobic digestion the management of the process would be somewhat simpler. It would be possible, for example, to load the water hyacinth plant into containers and spray them with bacterially loaded effluent from the main digestion process, or from some other cultivated source, and seal them. By carrying out this first stage outside of the digester it is possible to reduce the digester volume.

Reasons against biological treatment Both anaerobic and aerobic pre-treatment are similar in nature. The advantage of anaerobic digestion is that it would commence the actual process to be carried out whereas aerobic pre-treatment would start the decay of the organic matter in the wrong direction by inducing the growth a bacteria which would need to be destroyed and replaced in the anaerobic digestion process. The product of aerobic digestion will be carbon dioxide and that of anaerobic digestion will be, eventually, carbon dioxide and methane. The concern with both of these options is that any significant amount of decay of organic matter will reduce the overall performance of the system. It is likely that decay will commence most rapidly with those fractions of the organic material which would be the most productive in the anaerobic digester itself. The refractory components, such as lignin and hemicellulose, would tend to be resistant to bacterial pre-treatment whereas, the lipids and the cellulose would tend to be fairly readily consumed. It is this separation of readily digestible, moderately digestible and slowly digestible fractions which tends to indicate that biological pre-treatment is not a realistic option.

Mechanical pretreatment

Principles The basic principle involved in mechanical pre-treatment is similar to that with chemical pre-treatment and biological pre-treatment. The objective is to remove part of the process of anaerobic digestion outwith the digester, thereby reducing the volume of the digester and accelerating its performance. In the case of mechanical pre-treatment this is achieved by increasing surface area. The bacteria in the digester have as one of their major constraints on performance, the surface area that is available for attack. If the surface area can be massively increased, then it is reasonable to assume that the performance of the bacteria will likewise be massively increased. Certain forms of mechanical pre-treatment achieve a similar objective to that of chemical and biological pre-treatment by mechanically carrying out the process of solubilisation.

Chopping In the case of chopping the plant would typically be reduced to portions of approximately 1-2 cm in length. In Bangladesh, as part of this study, the chopping of water hyacinth stems was carried out by a mechanical chopper which enabled uniform fibre length from the stem portion to be achieved. The question of fibre length is one to which attention must be given. Should short fibre lengths be acceptable for other purposes then closer cutting would be advisable. By chopping the plant, as has been mentioned above, the surface area available for attack will be increased. However, chopping does not in itself assist in the breakdown of the structure of the plant and the reduction of its refractory nature. The fibrous surfaces of the stem would remain largely intact.

Crushing Crushing the plant is somewhat the contrary to chopping the plant. By crushing the plant the structure of its cells is broken down in such a way that the surface is increased. The fibre length, however, is not necessarily damaged at all. Where longer fibres are required this is an option that should be considered. The increase in surface area would be significantly greater by passing the feedstock through a pair of crushing rollers than it would be by chopping it.

Slurrying In the case of slurrying the whole plant is effectively minced and reduced to a minimum practical unit volume. The product from a slurrying process would be a viscous liquid in which the surface area is maximised and the mechanical solubilisation of the soluble organics is likewise maximised. Where the fibre length is not of concern, the process of slurrying is likely to be preferred to crushing and chopping. Slurrying of the whole plant, including the roots, will also make the root fraction amenable to digestion. As has been demonstrated in the current work, the root can in actual fact contribute a greater percentage of COD than the stem. It is, therefore, desirable that the root should be included in the overall process and that it should be reduced to a form which makes it amenable to anaerobic digestion. This can be achieved with the slurrying process.

Pressing Pressing the plant to extract the juice and separate out the fibrous portion is an option which needs detailed investigation. In principle it has been found that the uncontrolled pressing of water hyacinth slurry will not allow a significant transfer of COD from the slurry to the juice. In the current trials a loss in COD to the order of 50-75% resulted when pressing slurry. However, the detailed control of the pressing process is one which requires further careful analysis. If the slurried water hyacinth is pressed in thin layers then the amount of juice per unit that is achieved increases and likewise the COD in the juiced water hyacinth is increased. In the case of leaf, for example, very high juiced leaf concentrations were achieved. This is because the leaf portion contains a lower percentage of lignin and hemicellulose and the retention of solubilised matter is, therefore, reduced. In the case of stem, the matting of the fibrous content acted as a break on the pressing process and it proved not possible to compact the slurried stem to a degree sufficient to extract the maximum quantities of juice. The overall trade off between increase in operating plant performance and loss of COD at the juicing stage is one that forms a principle part of this thesis.

Cost implications The cost of each of these mechanical pre-treatment processes is not insignificant. Work carried out at Mahidol University in Bangkok, Thailand, has determined that the energy cost per tonne of water hyacinth would be to the order of 2.7 MJ electric for the slurrying process. The pressing process, being in need of further evaluation, would again require additional energy input. In the case of the work carried out at Mahidol, it was necessary to employ manual labour to carry out the pressing process and this is acknowledged as being highly inefficient.

The research work carried out in the Housing and Building Research Institute in Dhaka involved chopping the stem portion of the plant with a mechanical chopper and then beating the chopped stems with a pulping machine. This was found to be rather inefficient. The separation of the leaf and the roof portion to enable the chopping process to work effectively proved to be disadvantageous to the overall process in various different ways. The motor employed in the chopping plant in Dhaka was 1.5 kW and its throughput was approximately 50 kg/hr. The beater machine employed a motor of 15 kW and it was necessary to run it for an hour to effectively beat the 50 kg of chopped stems. The resultant total energy requirement (assuming absorbed power equals 80% the rated power) for one tonne is thus to the order of 47.5 MJ. This is clearly not an acceptable method of mechanical pre-treatment when compared to the method used in Bangkok. The question of mechanical pre-treatment costs is one to which we will return later in this thesis.

<u>Reasons against mechanical pre-treatment</u> The primary objection to mechanical pre-treatment is one of energy costs. Apart from this factor the mechanical pre-treatment of water hyacinth has a lot to commend it. It makes the root portion of the plant amenable to anaerobic digestion, it reduces the blocking effect of the refractory portion of the plant such as the lignin and the hemicellulose by reducing the fibre length to a minimum, or removing it completely in the case of juicing, and it solubilises and breaks down the cell structure of the plant in such a way that the surface area is increased enormously for the consumption of the organics by anaerobic bacteria. Given these advantages, and setting them against the disadvantages, it was felt necessary to investigate the options for mechanical pre-treatment further.

Pre-heating

<u>Principles</u> There are two principle temperature ranges in which anaerobic digestion may occur - mesophyllic (30-35°C) and thermophilic (40-45°C). In tropical climates the ambient temperatures tend to vary around the lower end of the mesophyllic range. It is well established that as the temperature is increased the rate of anaerobic digestion also increases. A complication with regard to temperature is that as the ambient temperature in which the bacteria are operating increases the bacteria become more sensitive to temperature change. In the mesophyllic range the bacteria can tolerate a $\pm$ 2°C variation in their environmental temperature. In the thermophilic range the tolerance is $\pm$ 0.5°C. It is, therefore, very important that should a high temperature

range be adopted for anaerobic digestion the temperatures are maintained constant. By pre-heating the feed to the digester, it is possible to work in a higher temperature regime. This in turn means that the rate of the whole process may be increased. In a tropical environment operating within a system structure as outlined in this thesis, there are a number of sources of heat energy that are readily available. These are solar energy, gas fired energy and solids fired energy.

Solar Pre-heating In the case of solar pre-heating, it would be the objective to transfer energy available in the form of sunlight into the feedstock to the digester. This may be accomplished by various means. Direct solar heating would involve arranging the feedstock in such a way that it is heated as it passes into the digester. It would probably be desirable to have some form of buffering, and a solar collector containing an internal loop of high heat capacity liquid, would enable the solar panel to operate for periods when the sun is not shining. It is, however, unlikely that the quantities of heat that would be required to create a significant impact on the overall process could be attained from solar heating. One square meter of solar panels will collect, at best, approximately 750 watts. In terms of the throughput required by a large scale anaerobic digester this is a trivial amount of energy. To raise the temperature of one tonne of feed from (say) 25°C to 35°C will require an energy input of approximately 42 MJ. If achieved over one hour the theoretical power input, excluding inefficiencies, is 11.7 kW, equal to 15.5 m^2 of solar collector area.

The real problem for solar energy comes during those periods when the sun is not shining. If the digesters are intended to operate on a twenty-four hour basis, the temperature of the feed will need to be achieved by means of some other form of energy input. Whilst it is acknowledged that it would be possible to devise methods of buffering and managing the solar heating of the feed, the overall effect would be to make the process more complex and less stable. When it is considered that tropical countries have ambient temperatures which will enable a digester to operate for most of the time in the mesophyllic range, a preferable objective would be to arrange the digestion so that no additional heat input is required.

Gas fired pre-heating One method that may be considered to supplement a system of solar pre-heating is to use a portion of the gas produced from the anaerobic digestion process itself to pre-heat the influent feedstock. A ready calculation can demonstrate the overall efficiency of such a process. If the operational temperature of a one tonne digester is increased by 10°C the amount of heat input required will be 42 MJ. This is equivalent to 2 m^3 of biogas. The gas produced per tonne (wet weight) of water hyacinth is approximately 22.5 m^3 and, therefore, it will require 8.8 % of the feedstock to heat the influent by

10°C. This rudimentary calculation does not allow for process inefficiencies, the most notable of which may be the volume of gas produced per wet tonne of water hyacinth. It may be that under certain circumstances such a recycle of the energy would be appropriate.

Solids fired pre-heating The process of juicing, as elaborated subsequently in this text, results in the solids contents, in the form of lignin and hemicellulose, being separated from the remainder of the readily solubilised biomass. The solids residue from water hyacinth will have an energy content typically in the region of 10 MJ per kilogram. Taking the above example, to raise the temperature of the digester by 10°C will require 42 MJ per cubic meter of water. It will require 4.2 kg of solids to provide the heat input and this will be obtained from 80 kg of wet feed. It must be noted also that the solids have first to be dried and this itself would require an energy input. Such a method of pre-heating would only be appropriate where the fibrous residue from the juicing process has no value.

CHP The possibility of using combined heat and power is a real one. It is envisaged that one of the major products from the overall process will be electricity. If this electricity is generated with a gas fired internal combustion engine the waste heat from the electricity generation will be available for heating the digesters. Internal combustion engines operate in the efficiency range of between 30-35%, in the case of spark ignition engines. This means that for every 1 MW of electricity produced there are typically between 1.5-2 MW of waste heat available for process heating. A properly designed system of heat exchangers would enable the anaerobic digesters to be heated and to assist the overall efficiency of the plant by operating as a heat sink. Should the heat sink not be in the form of the digesters, it would probably be necessary to use electrical energy to drive fans to cool the plant.

Heat exchange Where energy is employed to raise the temperature of the overall process, a further opportunity for improving efficiency would be to pass the effluent from the digester counter-current with the influent. This would ensure that the maximum amount of energy was retained within the digester. Counter-current heat exchange combined with CHP and perhaps some other form of energy input would help maximise efficiency.

Reasons against pre-heating The major problem with pre-heating is that the cost/benefit ratio may not prove to be viable except in the case of CHP and heat exchange. It would be necessary to raise the temperature of the digestion process from the lowers 30's typically in Bangladesh or Thailand in the cool season, up to the lower to middle 40's required in thermophilic digestion. Increasing the temperature of the process by 15°C would in itself result in a dramatic improvement of the overall plant performance. However, to raise the temperature of the feedstock by 15°C would require 63 MJ per cubic meter. Similarly, with solid fired pre-heating the fuel burnt to increase the process efficiency could be more effectively employed elsewhere. Only in the case of CHP would it appear that viable heating of the process could be achieved. The disposal of the waste heat would itself be advantageous in that it would increase the overall plant performance efficiency.

Varying the water content

Principles As with other methods of pre-treatment, it is possible, by adjusting operating parameters, to improve the overall operational efficiency by varying the water content of the feedstock. As indicated, water hyacinth is a very low solids content feed, typically having 95% moisture content in the harvested plant. By reducing the water content it becomes possible to consider the application of high-rate/high-solids digestion processes, such as the Valorga process, or other such systems that have been developed in the last ten to fifteen years. On the other hand, by further diluting the solids content it becomes possible to adapt the feedstock to structured designs which encourage mixing and bacterial movement within the digester. The problem with water hyacinth is that its basic form means it cannot be readily employed in either high-solids or low-solids digesters. In low-solids digesters the lignin and hemicellulose content tend to promote blocking, whilst in high-solids digesters the actual low solids content means that returns may be very low compared with the cost of the technology required to operate the process plant. There are a number of methods available for varying the water content, including utilisation of solar energy, as well as juicing the feed.

Sun drying Work carried out in the Sudan has demonstrated the overall performance of sun drying. It has been demonstrated, that in order to reduce the water content of the feed from 92% to 20% it is necessary to leave the plant in an exposed solar-irradiated position for a period of five days (Koser, 1982). This does, in fact, bring the water hyacinth in the range of the high-solids digestion process. If a through put in the region of 100 tonnes of water hyacinth per day is considered, and the solar irradiation requirement is five days, then it will be necessary to have a holding area which can cater with 500 tonnes at any one time. As has been found in the Sudan experiment, the cost of moving and transporting this tonnage of wet and partially dried water hyacinth very significantly indents on the overall system performance.

Dilution Dilution would reduce the solids content to a point where the lignin becomes insignificant and not a cause of blocking. However, the refractory nature of the lignin portion of the plant ensures that no matter how much dilution is employed, the first stage of anaerobic digestion, hydrolysis, will not occur unless some form of pre-treatment is employed which ruptures the tissue material of the plant and allows a greater surface area for bacterial attack. Dilution on its own will not contribute anything to the overall performance of the system.

Juicing In the case of juicing, the solids content will be reduced. This involves slurrying followed by some form of pressing. The requirement here, is that the reduced solids content of the feed will contain the more readily digestible portion of the plant. By increasing the relative proportion of readily digestible elements, the overall system performance will be increased. A further advantage of juicing, which has been alluded to above in the text, is that the residual material may have other uses.

Reasons against varying the water content The water content of water hyacinth is high. There is a possibility that its further reduction may lead to a less efficient process. This trade off between solids content and overall system performance is one that will receive attention in the experimental part of this thesis. Employing some form of heating to dry the feedstock is likely to be of dubious efficacy. A considerable amount of effort and energy is required to reduce the moisture content and, once reduced, it then requires increased amounts of energy to process the dried material through a high-rate anaerobic digester. High-solids, high-rate anaerobic digesters are more energy intensive than low-solids digesters. A low-solids, high-rate anaerobic digester requires a pump able to provide a feedstock flow rate sufficient to place it into the anaerobic digester. A high-solids anaerobic digester requires energy input to turn some form of mixing paddle. To convert a low solids feed into a high-solids feed would in this sense not be practical.

3.2.4 Digester options

There are a number of available techniques for anaerobic digestion and are discussed below.

Types of anaerobic digesters

i Simple plug flow
ii Plug flow with some reflux
iii Plug flow with 90% recirculation
iv Two stage plug flow with 90% recirculation at both stages
v Fully mixed systems
vi Systems with bacteria anchored to flow channels
vii Systems with bacteria dispersed in flow but not moving with the flow

Simple plug flow In a simple plug flow anaerobic digester there is no mixing and the flow is laminar. Retention time of the feedstock in the plant is calculated directly from the velocity of the feedstock on a path parallel with the walls of the digester. This is typical of the Khadi village industries type of digester widely found in India and China. The feedstock is placed in one end and the effluent is removed from the other end; there is no attempt at mixing or control. Retention times may be between forty and sixty days.

Plug flow with some reflux In an attempt to improve the efficiency of the process, effluent material is collected and placed back into the inlet of the plant. The reason for this is that the growth of methanogenic bacteria is very slow. Where feedstock is input into the plant un-inoculated with bacterial colonies, it is necessary for the bacteria to grow from the small numbers available in the environment. This in itself becomes a major constraint on the efficacy of the whole process. A small amount of effluent reflux will improve the performance of the simple plug flow digester considerably.

Plug flow with up to 90% recirculation This is one of the principles that is employed in high-solids high-rate anaerobic digesters. The principle here is to retain the bacterial colonies within the digester. With a high-solids digester it is not possible to separate out the effluent solids from the bacterial colonies, and therefore a high-rate of recirculation is employed in order to keep the bacterial colonies within the plant.

Two-stage plug flow with 90% recirculation at both stages Within the anaerobic digester there are two principle bacterial regimes. In the first regime, of hydrolysis and solubilisation, bacteria reduce the organic material to simple molecules that may be more readily attacked by the acetogenic and methanogenic bacteria. The presence of two regimes means that the first, is readily separated from the later stage of methane formation. By splitting a digester into two portions, it is possible to maximise the efficiency of each stage. Such two stage processes have been employed in high-rate anaerobic digesters. By employing a high degree of recirculation at both stages, it is possible maintain the bacteria relevant to that stage within the process.

Fully mixed systems In the case of fully mixed systems the retention time of influent material will vary. There will be a Gaussian distribution of solids retention time. Fully mixed systems usually employ some form of paddle or blade which circulates the contents of the digester. Incoming material will be mixed fully into the body of the liquid and it is for this reason that some incoming material will pass immediately to the effluent. By mixing the system in this manner, it is possible to maximise bacterial contact with the incoming biomass and thus the system's performance is dramatically increased. One of the drawbacks of such a system is that the two stages of anaerobic digestion, namely hydrolysis and methane production, are not separated out, and this in itself causes some reduction in overall system performance.

Systems with bacteria anchored to flow channels In this case, commonly referred to as the fixed film bacteria system, bacterial colonies are retained in the digester allowing them to fix to the flow channels walls or other surfaces within the anaerobic digester. This type of anaerobic digester is only suitable for soluble or low solids feed. The anaerobic bacteria are retained within the digester and, therefore, the overall system performance is increased. As a contrast to fully mixed systems however, the bacterial colonies will develop in those areas in which they are most appropriately employed. Therefore, the fixed film with hydrolytic bacteria will be formed in the early stages of the anaerobic digester, whereas in the latter stages prior to exiting from the digester the bacteria will be methanogens.

Systems with bacteria dispersed in flow but not moving with the flow There are a number of methods of achieving this, the sludge blanket digester being an example. Here a blanket of sludge is encouraged to develop in the path of the flow through the digester. The sludge itself is, therefore, rich in the bacteria which will carry out the various processes at the correct point in the reduction of biomass. A more sophisticated form of digester which matches this principle is the up flow anaerobic sludge blanket as well as the multi-stage upflow reactor. Both these reactors encourage the formation of granules or flocks of bacterial matter. The granules sit in the flow stream of the plant and attack biomass passing through the flow channels, this is the basic principle of the high-rate low-solids anaerobic digestion process.

Problems with high-rate anaerobic digestion

Low solids The essential problem with low-solids, high-rate digestion is that it is currently only applicable to soluble substrates. To transform water hyacinth into a feedstock that will behave as a soluble substrate, without incurring complex pre-treatment, is the object of current research. Pre-treatment methods being examined include maceration, juice extraction, chopping and pre-digestion. The possibility of acid or alkali pre-treatment has been considered (see para 3.2.3) but can only be applied to the detriment of the overall economics and operational simplicity. Another approach to this problem is being made by considering the possibility of anaerobically degrading the lignolitic component which holds the cellulose and hemicellulose components in structures which result in blockages by the use of rumen fluids. (Grobicki, 1988) To avoid such blockages the solids content of a water hyacinth feed normally has to be held quite low (eg.2%) compared to those encountered with soluble substrates. Solids loadings of up to 10%

can be found in soluble feeds.

The principal requirement is to establish a workable high-rate digestion process route for water hyacinth. This will involve establishing which of the pre-treatment options available is optimal to the high-rate digestion criteria and the scale of application. The need for pre-treatment techniques may be obviated if bacterial colonies can be developed specifically to reduce the problems that will result from digester blockages.

Within the socio-economic framework there are a number of obstacles that will need to be tested with a suitably designed pilot programme. For example, it has often been remarked by Bangladeshi researchers that although water hyacinth is a currently viewed as a nuisance, as soon as it is generally perceived that it has a use it ceases to be available, except at a price. This in itself is not necessarily be a bad development if the 'owners' of the water hyacinth can be persuaded to supply it at a price which matches the cost of harvesting. Exactly how such factors will work through remains to be seen.

High-rate anaerobic digestion processes designed to accept low-solids feeds would normally have up to 90% water content. This in turn implies that the processes are fluid and will readily mix should agitation of some form or other be applied. One of the problems with low-solids digestion processes is that any degree of solids content will lead to blocking of the flow passages in the digester. Any such blocking will occur in a manner which initially leads to a channelling and short circuiting of the digester volume. Such channelling reduces retention time and overall digester efficiency.

<u>High-solids</u> High-solids anaerobic digesters, by contrast, typically have a solids content of up to 50%, the balance being water. With high-solids anaerobic digesters the processes are designed around the fact that ready mixing is not achievable without the input of some form of energy. A high-rate digester has been produced in the United States which relies on a leach bed approach. Solids in the digester are retained in one vessel and the methanogenic reaction is developed in a second vessel. Work carried out with water hyacinth employing this principle discovered, however, that the majority of the digestion occurred within the leach bed, rather than within the designated methanogenic reactor (Tenscher, 1989). Other forms of high-solids anaerobic digesters employ gravity to assist with mixing and high power paddle mixers. One of the principle requirements of a high-solids system is that there is a high degree of recirculation, to retain bacteria within the process.

<u>Energy requirement</u> With low-solids reactors, the energy requirement is simply that for pumping water to the hydraulic head of the plant in

question. With high-solids reactors the energy requirement is usually greater. In the case of the leach bed approach the retention time would in fact be less than is attainable with some of the new forms of low-solids reactors. Consideration has been given to the possibility of using water hyacinth as a high-solids feed in view of its bulking characteristics and the fibrous matting which occurs when the plant structure is reduced by bacterial attack. In practice however, this would not be viable. The water hyacinth has a low solids content and would not produce the quantities of biogas that are able to justify the energy input to a high-solids reactor.

Suitable designs for water hyacinth Despite successful laboratory trials on water hyacinth, at present there are no suitable high-rate digestion processes available for commercial use. This has been acknowledged by other researchers, the response generally being to accept this fact and to work with existing proven designs, rather than expend the effort in evaluating suitability of high-rate designs (Pillai.1983)

Suitability of existing designs for use with water hyacinth as a feedstock

The Upflow Anaerobic Sludge Blanket Reactor (UASB) The UASB is widely employed in various parts of the world for treating various forms of organic effluent. It has been employed on sewage sludge effluent from food processing and other forms of industrial effluent. There are a number of problems however with the UASB that would make it difficult for water hyacinth to be used without some form of modification to its structure. The UASB is essentially a liquid process with the feed being displaced by hydraulic head up through the body of the reactor. The high contact obtained is enabled by mixing through recirculation within the upward flows. In order to obtain a high decree of efficacy the UASB tends to be a tall column. Whilst the height of the column in itself does not rule out the UASB as a digester for water hyacinth it is a significant element in the cost to benefit ratio that must be carefully analyzed when considering the commercial use of water hyacinth.

The multi-stage upflow reactor The multi-stage upflow reactor is a series of up-flow channels contained within one single volume; it has been described as a series of UASBs. The advantage here is that increased mixing is achieved without a significant increase in height. With the multi-stage upflow reactor the height requirement is removed. A further advantage of the multi-stage upflow reactor is that the various stages in the digestion process are separated out, so that, for example, the initial hydrolysis can be kept separate from later methanogensis. When it comes to employing the multi-stage upflow reactor for water hyacinth the problems of the UASB are amplified many times. The feedstock will not flow through the plant without causing a great deal of blocking. Experimental work in Bangladesh demonstrated this problem. Despite the fact that water hyacinth stems were chopped to an average length of 3 cm it was not possible to cause the material to flow through the reactor.

Summary Unless the water hyacinth is modified in some form or other it will not be possible to employ the plant effectively on a large scale. This has been amply demonstrated by numerous researchers. Where high-rate or approaching high-rate anaerobic digestion has been achieved, it has usually been by some form of serious alteration of the feedstock condition. For example, researchers in Assam in Indian, and others working on the same United National Environment Programme, project dried and ball-milled the water hyacinth prior to placing it in fully mixed reactors. Drying and ball-milling water hyacinth would be very difficult to achieve commercially.

High-rate anaerobic digestion of water hyacinth

Why it is desirable With a low solids content and a high water content, combined with a high proportion of lignin the batch anaerobic digestion of water hyacinth is extremely slow. In order to develop a process which optimises the benefit that may be obtained from the organic content of the plant, it will be necessary to process high volumes of the feed. One essential ratio is that of capital cost to energy output. If the digester volume is increased by fifty fold, it is probable that the capital cost will be increased by a similar order of magnitude. With large volumes, as with tall structures, the civil engineering required becomes more sophisticated and therefore more expensive. The objective of a high-rate anaerobic digestion process for water hyacinth is one that will be key to the successful application of a biogas progressing route.

Options on feedstock condition As has been discussed above, there are various methods which may be employed for pre-treating water hyacinth. In the case of pre-treatment to match high-rate anaerobic digestion, it is likely that chemical pre-treatment and biological pre-treatment would have no appreciable affect on the suitability of the feedstock. In order for chemical pre-treatment and biological pre-treatment to sufficiently alter the structure of the plant and its mechanical properties, to enable it to be employed in a low-solids high-rate process, it would be necessary in the former to employ some very high strength chemical solutions, and in the latter to leave the plant for a considerable amount of time. High strength chemical solutions will be expensive and excessive time in biological pre-treatment will significantly reduce the availability of easily digestible material for the anaerobic process. The option of varying the moisture content of the plant is one that introduces greater possibilities. In the case of high-solids digesters sun drying would concentrate the organic solids and thereby facilitate the use of the more energy intense process. However, as has been discussed above, the problem of drying water hyacinth to 50% solids content is one that will require high energy input, or large areas of ground plus high energy input into the transportation of the plant in the drying fields. Employing mechanical pre-treatment would therefore remain as the principle option for feedstock preparation for high-rate process. Mechanical pre-treatment will be readily facilitated in a single location and may be achieved with a comparatively small energy input. There are a number of options for mechanical pre-treatment, as have been discussed above. The slurrying of the plant can be arranged in such a manner that the fibre lengths are reduced to a level where they are not significant. Experiments carried out with drying and ball-milling reduced the water hyacinth plant to a powder. Work carried out in Thailand employing a mincing process, reduced the water hyacinth plant to a liquid slurry which might possibly be amenable to certain forms of high-rate processing.

Relevant designs Taking the mechanical pre-treatment stage as being that which will most readily adapt water hyacinth for high-rate processing, there are a number of options to be considered. The UASB would be suitable for use with slurried water hyacinth. It may be pumped vertically through such a system and it is likely that it would not significantly mat or block. The UASB would also perform very well with a juiced water hyacinth feedstock.

The multi-stage upflow reactor would in all probability, not perform well with slurried water hyacinth. The requirement for the plant to flow both up and down through vertical channels would in all probability result in serious blocking. The multi-stage upflow reactor would, however, be suitable for use with juiced water hyacinth. The reduced solids content would make the feedstock amenable to the mixing strategy employed within the multi-stage upflow reactor process.

Reactor design with respect to feedstock condition

The ideal scenario would be to design a high-rate digester which matched, as closely as possibile, water hyacinth feeds requiring minimum preparation. This would enable the overall process to reach an optimum state of productivity.

One of the fundamental principles of high-rate digestion is that there should be maximum surface area for contact between the biomatter within the feed and the anaerobic bacteria. It is, therefore, not possible to avoid the requirement to break the plant structure in some form or other to increase the surface area available to bacterial attack.

A further requirement for anaerobic digestion is that mixing should be take place within the various stages of the anaerobic process. This ensures that bacterial contact is maximised.

Given these constraints, it is difficult to envisage systems other than those that currently exist for the high-rate digestion of biomatter. It may be that certain refinements may be introduced to adapt existing designs to the feedstock conditions that could be available, and this point will be addressed later in the thesis. The real challenge, however, is to arrive at a feedstock condition which will be suitable for existing designs.

The UASB vs the multi-stage upflow reactor

Vertical vs horizontal The cost of installing the reactor is one of primary concern. Once the question of volume has been addressed and minimised, it follows on that the engineering structure itself will be one that should be optimised. The UASB, being a vertical structure, will require significant engineering to erect. Designs currently operating in Italy would amply demonstrate this point. Vertical structures will have significant advantage where land value is at a premium. For example, in the centre of Tokyo, should it be necessary to construct a reactor of some form or other it would ideally be as narrow as possible and as tall as possible, given the fact that one square inch of ground has a typical price of approximately £2,000-3,000. However, the avoidance of vertical structures is taken to be a general improvement on overall process economics. The multi-stage upflow reactor, being a horizontal arranged series of baffles, will, therefore, require a lesser degree of engineering. The plant in this form will also be more readily accessible for maintenance and any necessary clean out or repair that may be required.

Productivity By its nature the multi-stage upflow reactor will tend to induce a greater amount of mixing within the feedstock as it passes through the unit. This will enhance its performance over that of the UASB. In the UASB mixing will occur by the nature of the flow through the unit. If it becomes a vertical laminar flow the amount of mixing will become minimal. A further advantage of the multi-stage upflow reactor is the separation of the various stages of the anaerobic digestion; by keeping the methanogenic bacteria separate from the hydrolytic bacteria for example, the overall performance will be increased. Hydrolytic bacteria will concentrate and perform the hydrolysis more rapidly. Similarly, in the methanogenic stage, the pH will adjust to suit the optimum environment for methanogenic bacteria and methanogenesis will occur more rapidly. It is, therefore, not unreasonable to infer that the multi-stage upflow reactor will have a greater productivity than the UASB.

Start-up Work to date has suggested that the multi-stage upflow reactor will start more readily than the UASB, which requires a thirty day gradual and controlled start up. The formation of granules within the multi-stage upflow reactor occurs more readily than within the UASB. Indeed granule formation within the UASB is sufficiently difficult to achieve that a market has developed for their manufacture and sale.

Cost implications All these factors add together to cause the multi-stage upflow reactor to be a less expensive system to construct and operate. The engineering of the structure will be lower, the volume required will in all probability be smaller, although not significantly so, and the start-up will occur more rapidly. Start-up costs will mean lost production and increased over heads.

Problems with the multi-stage upflow reactor When it comes to considering the use of the multi-stage upflow reactor as a process for conversion of water hyacinth to biogas there are a number of problems which must be addressed. The primary amongst these is the feedstock condition. As has been mentioned above, the multi-stage upflow reactor will not readily accept anything but the most soluble organic waste streams. It is specifically intended for such feedstock streams. Build up of solids within the multi-stage upflow reactor will rapidly lead to channelling and short circuiting of the whole process. This will lead to major deficiencies in plant performance. This requirement for a soluble organic feed is one that may be difficult to achieve with the water hyacinth. By slurrying and pressing water hyacinth the more readily solubilised components are concentrated, but together with these there will be insoluble solids. There is a possibility that these insoluble solids may cause problems in the operation of the multi-stage upflow reactor. However, this difficulty is more readily amenable to an engineered solution than would be the case with slurried plant. In the case of slurried plant the non-soluble solids are of such a high proportion that the feed would not flow at all.

Problems with the UASB and why it is not considered further In summary, the UASB will require a higher capital cost for construction. It will be less productive than the multi-stage upflow reactor. It will be more difficult to start up and it will have an overall lower efficiency. Having said this, there is a possibility, which may need to be addressed further elsewhere, that the use of slurried water hyacinth in the UASB would be a method of obtaining a greater through-put. The reduction in productivity and the increase in cost might be offset against the higher organic content available for digestion. As will be seen in Chapter 5 of this thesis, the slurried water hyacinth typically had a solids content of approximately five times that of the juiced water hyacinth. A high-rate process, which can effectively handle slurried water hyacinth may, therefore, be one which proves to be more efficient economically.

Why the multi-stage upflow reactor looks more promising In the context of the overall system however, the separation of the fibrous portion of the plant from the more soluble organics will be one that has advantages in itself. By separating out the fibre prior to digestion, rather than after digestion, the overall system performance is likely to be increased. The requirement for separation of fibre and prodiuction of soluble feed, therefore, leads to the use of the multi-stage upflow reactor on a juiced water hyacinth feed. It is for this reason that the multi-stage upflow reactor will be investigated in greater detail in subsequent chapters.

3.2.5 Gas collection and use

In 1988 the proven reserves of natural gas in the world were equivalent to 100 Gtoe, which is approximately equal to two-thirds of the crude oil reserves. The current demand for gas on a world wide basis is 1.7 Gtoe per annum and it is likely to steadily increase as more natural gas is used as a substitute for oil, particularly for electricity generation (Eden, 1991). To put this into context, it is necessary to anaerobically digest six tonnes dry weight of water hyacinth in order to produce one tonne of oil equivalent. This in turn is approximately equal to 100 tonnes wet weight of harvested plant, or the annual product from one half hectare in Bangladesh. The current world natural gas consumption is equivalent to the product from an area of water 3,000 km by 3,000 km. The technology for the use of gas is in a state of rapid development and it is likely that the rate of application will increase as oil reserves become less available.

Local use uncleaned

The collection of biogas from the anaerobic digester is a relatively straight forward technological problem. It is necessary to set pressure heads that to ensure the gas is delivered at a suitable pressure for subsequent use. The most attractive method of using biogas is to burn it local to the point of production for a process needing service heat. In the case of domestic biogas production units, the biogas is typically used for cooking or lighting. In the industrialised countries where biogas is collected from sanitary landfills, its most attractive form of exploitation is direct burn in, for example, brick kilns or to raise steam. A number of such schemes in the UK, Europe and in the United States stand un-assisted as viable commercial ventures. Their only problems develop with the fluctuation in the world price of oil and gas. This is a common problem for all forms of energy production, and one which will remain. The value of the local gas product is intimately related to considerations far outside the control of individual societies.

Local use cleaned

The cleaning of biogas to remove carbon dioxide and traces of hydrogen sulphide, leaving a pure methane gas, is one which may be achieved with established technology. In numerous parts of the world biogas from landfill sites is cleaned by various techniques such as pressurised water scrubbers or pressure swing absorbers using zeolite beds and subsequently employed as a vehicle fuel. The filling stations are typically located adjacent to the point of production of the gas and transport costs are, therefore, minimised. The cleaning and dispensing of methane to vehicle use, only becomes attractive as the price of oil increases. It is likely in the immediate future that the price of oil will not increase dramatically. However, as the finite reserves of oil in the world begin the decline and the stresses between various social blocks increases, there is a high probability that oil will become a difficult fuel to obtain. This being the case, the industrialised countries are likely to be able to afford the higher prices, and the developing countries to be pushed more towards the use of gas. In this scenario the possibility of using water hyacinth locally-produced biogas as a vehicle fuel will become more attractive.

Transport to point of use

Where is it intended to transport biogas to a remote point of use, there are a number of techniques available. Such techniques have been developed for use with natural gas. The world trade in gas is one that has fluctuated during the course of the last twenty years, but the technologies are well established. Prior to discovery of gas in the North Sea, British Gas used to buy tanker loads of liquified natural gas from Algeria. This gas was shipped in ocean going tankers and stored at Canvey Island. The cryogenic transport of methane is, however, not one to be considered unless scales of use are at maximum level. Cryogenic methane is produced by dropping the gas temperature to approximately -180°C. It is not possible to liquify methane by compression alone, as the triple point is below zero. The problem with a liquid gas held at -180°C is that no currently available technology will fully insulate the liquid from the ingress of heat. For this reason there is a slow but predictable build up of the temperature and the consequent boil off of the gas. Typically a cryogenic tank will have a boil off rate of between 1-1½% per day. This means that after approximately 60-100 days there will be no gas left in the vessel. Large scale transport of liquified natural gas relies on systems which capture the boil-off gases and re-liquify them by cryogenic liquefaction techniques. On a large scale such boil-off re-liquefaction becomes feasible, but on a smaller scale it is impractical because the energy cost involved in re-liquefaction outweighs the value of the product gas. It is, therefore, unlikely that cryogenic techniques will be employed for the transport of biogas derived methane.

A further option for transport is that of compression, and indeed this is used when biogas is locally cleaned and filled direct to vehicles. Using compressed methane to propel a vehicle is, however, somewhat different from using a vehicle to transport compressed methane. In order to compress methane it is necessary to raise the pressure to around about 3000 psi. This involves a significant energy input. Once compressed to this pressure, it is necessary to store the methane in a high pressure vessel and these tend to be very heavy. The transportation of compressed methane, therefore, involves also moving a far greater weight of metal. It is unlikely that this would be a viable system for transporting biogas to a remote point of use.

A possibility which, although currently not attractive, may yet develop into a serious option is that of producing methanol from biogas. The production of methanol from natural gas and methane sources is receiving a considerable amount of attention. A plant built in New Zealand to convert natural gas to methanol, once it was finally constructed, was found to have cost an inordinate amount of money to convert methane to methanol with an overall efficiency of 50%. This means that half the gas is utilised in the conversion process. It is unlikely that this would become a serious option for any but the most particular of local circumstances. Technology in this area is moving rapidly and systems are available on the market for converting landfill gas from municipal refuse tips to methanol. Once again, however, the economics have not yet reached the point where it would stand alone in a commercial situation; without subsidies such techniques cannot yet be employed.

The principle method of transport of methane is likely to be via pipelines. Where possible, pipelines are employed all over the world. In this regard, one should be aware, however, of the drawbacks. A well recorded statistic is that of the number of leaks per kilometre. In Europe it is expected that, on average, there will be two leaks in a gas pipeline per kilometre, and that these leaks will tend to be small. Where larger leaks are encountered they are very rapidly repaired by the governing authority. By contrast, in the former Communist block countries, the average number of leaks per kilometre is between thirty-five and fifty. This in turn means that large quantities of gas are simply wasted. The scale of the problem is so large that no simple techniques are readily available to solve the problem. In the former East German states, techniques of relining gas pipes are being employed to prevent excessive waste. Such techniques are not available to other former Communist block countries, simply because of the cost. Viewed in this manner, it is not likely that gas pipelines in developing countries will fare significantly better than those of Communist block countries and the transport to remote use by pipeline should be very carefully considered with this particular problem in mind.

Remote use uncleaned

As with compression, transport via a pipeline involves an energy input. The transport of biogas with the typical composition of 40% CO_2 and 60% methane is unlikely to be considered seriously because of the energy required to transport the CO_2. Once again in certain specialised circumstances it may be that the CO_2 has an economic value but, unless this is the case, it would not be appropriate to transport biogas to a remote point of use.

Remote use cleaned

Once biogas has been cleaned by any of the various techniques that are available, it may be readily employed in any natural gas distribution network. In the United States biogas from landfill sites is occasionally cleaned to a point where it may be injected into natural gas pipelines. In the UK such an option has not in fact been employed because the quantities of gas are relatively small, the revenue that is available for sale of the gas to any of the gas companies is likewise small, and the standards required by the various gas companies is very high. It is, however, technically feasible and in a more equitable commercial environment would be commercially viable. Once cleaned to methane the uses for water hyacinth derived biogas are as many as those for natural gas.

Electricity generation

A principle use for biogas will be in electrical generator sets for the production of low and high voltage electricity. Once converted to electricity the distribution available is without limit in most societies. In developing countries the primary fuels available for electricity generation will be purchased in competition with industrialised countries and it is likely that fuels available for this use will be in the decline over the next century. For this reason it is envisaged that the local use biogas for electricity generation will become a primary application. A by-product from electricity generation is that large quantities of hot water are available, and it is to be expected that processes requiring hot water will be developed close to the source of such waste heat.

Chapter 4

THE BIOGAS PRODUCTION SYSTEM - DESIGN OPTIMISATION

As will be clear from Chapter 3, there are numerous process route options for the economic utilisation of water hyacinth. The following chapter assesses the potential for production of various commercial outputs and leads to the conclusion that biogas production is central to achieving maximum benefit from the exploitation of water hyacinth.

4.1 CHEMICAL COMPOSITION OF WATER HYACINTH

4.1.1 Analytical methods and measures

As well as energy, that has been the subject of comparatively recent interest (Wolverton,1975; Wolverton,1976; Lecuyer, 1976; Guha, 1976; Chin, 1978; Deshpande,1979; Sriramalu,1980; etc.), a number of other materials can be derived from water hyacinth. Various suggestions have been made for use of water hyacinth as a fertiliser, as a cattle feed, for compost, silage, a peat substitute and the preparation of paper, board and pulp (Sen,1929; Sen,1931; Sharma,1971; Jagadish,1971; Ramachandra,1971; Boyd,1972; Pieterse,1978; Mara,1976; Mazumdar, 1979; Yaduraj,1979; Pillai,1979; etc.). Prior to assessing the potential for the various possibilities a review will be made of the plant composition.

First, however, it may be helpful to clarify the meaning of the terms used in analysis of organic substrates (Barnes, 1981). This is important because an understanding of the tests available will be useful in seeing how the reported results of past experimentation and the experimentation carried out within this research programme relate to the objectives as stated in the proceeding chapters.

Total solids (TS)

To determine the total amount of solid material present in a water sample, a fixed volume of the sample is evaporated and the residue dried at 105°C and weighed. As no separation is involved, soluble materials such as sugar and salt are included in the result, together with clay particles and non-volatile oils.

Suspended and/or soluble solids

To determine the amount of material not in solution (the amount of suspended solids), the sample is centrifuged or filtered and the dried residue weighed. Soluble solids can be separated from the filtrate and then weighed, or they may be determined by subtracting the suspended solids from the total solids. The determination of suspended solids indicates the material which might be removed by a settlement process.

Volatile solids (VS) and/or fixed residue

If a sample is heated to 600°C in air, the organic material will burn and the weight loss can be attributed to the organic content of the sample. This is usually interpreted as the degradable fraction of the sample, although not all organic materials are degradable and some inorganic compounds, including calcium carbonate, decompose and lose weight at this temperature. The material remaining after heating is recorded as the fixed residue, or ash.

Settleable solids

The volume of settleable solids can be ascertained by permitting a sample to settle for a period of 30 minutes or one hour. The test is usually performed in a one-litre cone graduated at the base, known as the Imhoff cone. The values obtained are on a volume/volume basis, for example 15 ml/l, and not on the more usual mg/l basis. The test is incorporated into the sludge volume or sludge density index.

Biochemical oxygen demand (BOD)

This is the most widely used method for measuring organic pollution although the chemical oxygen demand (COD) and the total organic carbon (TOC) determinations are also used.

This test measures the oxygen required by micro-organisms during the degradation of a water sample. In a simple test, the dissolved oxygen concentration, DO, is determined at time zero, DO_o; another sample of the same wastewater is placed in a sealed bottle and incubated at 20°C for five days. During the incubation, the DO decreases and the DO_5 is determined. The 5-day BOD at 20°C is equal to the difference in the DO values.

Such a simple test is possible only for samples with a small BOD. The maximum dissolved oxygen concentration in clean water at 25°C is 9 mg/l. Samples can be diluted to increase the sensitivity of the test. This usually requires several dilutions of the sample to ensure that at least one dilution is of an appropriate concentration.

The BOD test is subject to the normal statistical errors of chemical analysis plus the errors inherent in projecting bacterial growth. For a standard solution (glucose and glutamic acid), an error of ± 5 per cent is normal; for actual samples, the error is usually much higher (± 10 to 20 per cent).

A second stage oxygen demand is often observed. In the case of raw or settled sewage, this second stage usually becomes apparent after approximately eight days of incubation at 20°C. In this second stage, oxygen is consumed in the oxidation of ammonia, producing nitrate ions in the process termed *nitrification*. A large percentage of the nitrogen in water and wastewater originates from proteins: the protein molecules are degraded to release ammonia. The oxidation of ammonia is carried out by two specialised bacteria - *Nitrosomonas*, which oxidises ammonia to nitrite ions, and *Nitrobacters*, which oxidise nitrite ions to nitrate ions.

$$2NH_3 + 3O_2 \xrightarrow{\textit{Nitrosomonas}} 2NO_2^- + 2H^+ + 2H_2O$$

$$2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacters}} 2NO_3^-$$

The process of nitrification consumes significant amounts of oxygen so that the total oxygen demand for nitrification is often comparable with the carbonaceous demand. Nitrification also generates protons, thus increasing the acidity of a water sample.

Chemical oxygen demand (COD)

The BOD method is lengthy and prone to difficulties with micro-organisms. A much faster chemical test, the chemical oxygen demand test, has been developed. Strong oxidising chemical reagents can be used to oxidise a sample, and the consumption of chemical oxidant can be related to an oxygen demand. Potassium dichromate is used in boiling concentrated sulphuric acid with a silver catalyst. Under these extremely strong oxidising conditions, organic material (plus some inorganic material) is degraded and the dichromate is reduced to trivalent chromium:

$$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$$

The oxidation is carried out for two hours, and the remaining dichromate is determined by titration with a solution of ferrous ion (Fe^{2+}). The difference in dichromate concentration between a blank and a sample solution is expressed as chemical oxygen demand (COD), conveniently determined as mg/l. Chloride ions can interfere with the test as they are oxidised to chlorine by dichromate and are registered as COD.

Because of the extremely strong oxidising conditions, the results of the COD test are usually higher than for a BOD test. The COD represents the complete oxidation of many organic compounds and some inorganic compounds. Ammonia, however, is not oxidised. As a first approximation, the COD can be taken as double the BOD. The actual ratio of BOD to COD varies from sample to sample. A reliable correlation can be made only if sufficient data have been collected to validate such a correlation.

Total organic carbon (TOC)

The determination of total organic carbon can be completed in a few minutes and does not require the use of wet chemicals. The results give the total concentration of carbon present as organic compounds in a sample. The technique involves combusting a small amount of the sample in air and measuring the carbon dioxide evolved. The results are displayed on a recorder. The instruments are provided with two separate reaction paths. One includes a low-temperature furnace (150°C) with an acid packing; a sample passed through this stream will yield carbon dioxide from the decomposition of inorganic carbonates. The carbon dioxide evolved from this low-temperature stream represents the inorganic carbon content of the sample. A second sample, passed through the high-temperature stream (1000°C), will yield carbon dioxide from the carbonates and from the combustion of organic compounds. The organic carbon content of the sample can be obtained by subtracting one result from the other.

This instrumental method is capable of producing results in a relatively short time (15 minutes). The method is very prone to sampling errors as it analyses only a small sample. The method is not related to biodegradability of the sample - a piece of plastic would register a TOC but not a BOD. The TOC is, therefore, a parameter different from both the BOD and the COD. The numerical value of TOC is likely to be lower than BOD, because it is the carbon which is being determined and not the oxygen consumption. (1g of C requires 2.2 g of oxygen to oxidise it.)

Choice of measure

In work carried out previously, the use of volatile solids (VS) as a measure of biodegradability has been commonly employed. The problem with this measure for use in the current work is that the incineration of organics at 600°C will burn out components like lignin and ligno-cellulose which are not amenable to high rate digestion. The BOD test, whilst offering the most appropriate method for assessing biodegradability, has the drawback of the time required to achieve results and the inherent sampling inaccuracy. In the context of both Bangladesh and Thailand, where experimentation was carried out, this test would have been unsatisfactory in its practical application. Whilst TOC would have been a useful means of assessing performance of the reactors studied, such an instrument was not available. A further drawback would have been that it would be difficult to relate this figure to previous work in the literature, without significant experimental setup. Whilst suffering a similar drawback to that of the VS test, in no differentiating between biodegradable and non-biodegradable organic carbon, the COD test has the great advantage of being relatively simple. The ready availability of the COD test in Thailand led to the bulk of the experimentation being monitored in terms of COD. The VS measure was taken occasionally and the ratio of COD to VS was taken as being fixed for any one particular substrate preparation. By this means it is possible to compare current work with previous work both by means of VS and COD.

4.1.2 Plant composition

The composition of the water hyacinth plant will vary with the location and nature of its growth. As has been mentioned previously, (Sect 1.2) it is possible to modify the proportion of root, stem and leaf by arranging such parameters as, for example, nutrient input composition and stand density (Singh, 1983). This will be an important factor in establishing a programme of cultivated growth.

Many studies of water hyacinth composition have been made during the course of the last century by researchers in different countries. This provides a wide range of information.(Table 4.1 and Table 4.2) The categories selected, and the varied analytical methods employed, provide differing assessments of the plant's basic components. Combined with incomplete details about the developmental stage, the growth medium and climate, the origins of the plant material are usually imprecise. The figures in Table 4.1 and 4.2 serve to indicate general principles, as opposed to defining conclusively the relationships between various components within the plant material.

The high moisture content of the plant has been noted previously. This is a dominant factor in any route to commercial exploitation. For each kilogramme of water removed by drying 3.5 - 4.5 MJ of heat will be needed. Where time does not represent an overriding cost, and solar radiation is adequate for drying, this energy may be obtained directly from the sun. Where this is not the case, the requirement for drying will significantly reduce the overall net benefit, should a process route involving drying be adopted.

Table 4.1 *A comparative analysis of various constituents of water hyacinth originating in India. (Sen. 1929; Dhar, 1970; Jagadeesha, 1971; Sarma, 1983; Srivastava, 1983; Pillai, 1983;)*

Characteristics	Sen	Dhar	Jag'sha	Sarma	Srivst'va	Pillai
% of whole plant						
Moisture	-	-	-	92.03	-	94.5
Dry matter	-	-	-	7.97	-	5.5
% dry weight						
Volatile solids	80.25	75.8	81.9	85.16	85.0	70-80%
Non-volatile solids (ash)	19.75	24.2	18.1	14.84	(15.0)	20-30%
Organic components % dry weight						
Protein (Kjeldahl N x 6.25)	9.9	9.4	16.5	9.7	22.0	27.5
Cellulose	21.89	-	-	-	21.2	24.7
Hemi-cellulose	-	-	-	9.60	33.8	27.7
Lignin	-	-	-	18.00	6.0	9.0
Lipids	-	-	-	-	2.0	2.1
Water soluble organic matter	23.64	-	-	18.2	-	8.6
C:N	29:1	17:1	-	32:1	-	-
Chemical components % dry weight						
Carbon %dm	46.5	-	-	49.40	-	-
Phosphorus %	5	0.68	0.43	1.20	-	-
Potassium %	1.23	5.32	4.25	6.68	-	-
Sodium %	5.25	-	0.34	1.60	-	-
Calcium %	2.02	2.86	1.00	7.56	-	-
Ether solubles %	1.85	-	-	3.50	-	-
Magnesium %	-	1.00	1.05	-	-	-

The non-volatile solids content is a significant element in a scheme where energy is one of the principle products. As well as the 90-95% moisture content there is ash (0.75-2.5% wet weight) which will contribute to the system output only as a fertiliser.

Table 4.2 *The composition of water hyacinth originating from the USA. (Finlow, 1917; Boyd, 1969; Lawrence, 1970; Easley, 1974; Para,1974; Para, 1975)*

Characteristics	Finlow	Boyd	Lawrence	Easley	Para	Para
% dry weight						
Volatile solids	75.8	81.29	-	-	80.8	81.7
Non-volatile solids (ash)	24.2	18.11	-	-	19.2	18.3
% dry weight						
Protein (Kjeldahl N x 6.25)	9.7	15.6	9.2	14.9	10.1	7.2
C:N	29:1	19:1	-	-	23:1	34:1
Chemical components % dry weight						
Carbon (calc'd) %dm	49.40	47.50	-	-	-	-
Phosphorus %	1.20	1.0	0.24	0.50	0.31	0.41
Potassium %	6.68	5.30	2.58	4.10	3.81	3.56
Sodium %	1.60	0.92	-	0.94	0.56	0.52
Calcium %	7.56	1.40	-	2.20	1.66	2.41
Magnesium %	-	-	-	0.59	0.56	0.78
Ether solubles %	3.50	3.5				

Hemi-cellulose and the water soluble organics indicate the levels of substrate that will be available for consumption by bacteria in the anaerobic digestion of water hyacinth. Once again, figures vary significantly. A more detailed analysis of water solubility, as shown in Table 4.3, provides confirmation that solubilities of oven dried water hyacinth are in the region of 15-20%. The comparatively high figure of 46.8% solubility in 1% caustic solution is worthy of note.

Very little information is available in the literature about the relative properties of the various portions of the plant. It is often taken that the roots will be of minimal interest in any scheme and they are usually discarded. During the course of the current work, however, it was noted that the root contributed up to 40% of the wet weight of the plant. Table 4.4 provides an insight into the relative value of the leaf and stem, separated from the root. Compared with the stem, the leaf has a lower moisture content, a higher protein content and a lower fibre content.

Table 4.3 *Proximate analysis (Ghosh, 1983)*

Characteristics	% (oven dry weight basis)
Cold water solubility	15.7
Hot water solubility	17.0
1% caustic soda solubility	46.8
Alcohol : benzene solubility	10.6
Lignin content	6.7
Pentosan content	14.2
Cellulose (Cross & Bevan)	29.0
Ash content	18.4

Table 4.4 *Average percentage (dry wt) of some chemical components of water hyacinth.(Meksongsee, 1983)*

Sample	Moisture	Protein	Fat	Fat pigment	Insoluble solids	ADF*
Leaf	89.2	24.9	2.9	0.30	8.4	20.8
Stem	94.7	11.3	1.6	0.27	4.6	33.3
Whole plant	93.1	16.0	2.1	0.21	6.2	28.2

* *Acid-detergent fibre, a ligno-cellulose which is almost indigestible by ruminants. (Gerpacio, 1979)*

4.2 PRODUCTS FROM WATER HYACINTH OTHER THAN BIOGAS

We wish to identify the various by-products from a system designed to produce useful energy, and to assess their relative merits. To achieve this, the options available for producing each potential product (fibre, fertiliser and protein) will be viewed in subsequent sections of this chapter with particular attention to the waste streams that result if each product is viewed as the single commercial output. Some of the products result in no waste stream relevant to energy production, but are included in this overview in order to set the various options in context.

4.2.1 Fibre production

The use of fibres from water hyacinth for products such as paper, board and baskets, etc. has been one that has received a great deal of interest in the last fifteen years. It has, for example, recently becoming fashionable to wrap "environmental" fashion products in water hyacinth paper. This development has occurred during the period of research involved with this thesis.

Fibre properties

There are several methods of assessing the value of the fibres in water hyacinth. Table 4.5 below is a comparison of various sources of fibre. The average dimensions of the water hyacinth fibre are somewhat misleading as the same study from which this table is taken also provided a minimum diameter figure of 1 micron and a maximum of 20 microns (Table 4.6). Presented in the manner of Table 4.5, the water hyacinth fibre appears to be similar in physical characteristics to that of jute. An interesting point to note is the similarity of water hyacinth fibre to straw fibre. The latter is not noted for its use as a fibre, although straw paper is manufactured in limited quantities for specialised markets. A study of the strength of products manufactured from water hyacinth demonstrates that, whilst in many applications it is acceptable, it does not possess any superior physical characteristics. Its use would, therefore, be predicated by the cost savings that may be achieved, rather than any unique qualities.

The bulk of the fibre to be found within water hyacinth is in the stem. It is for this reason that schemes intent upon using water hyacinth as a source of fibre usually commence with the separation of the stem from the root and leaf portions of the plant (Hannan, 1983).

Fibre separation processes

Table 4.8 describes the various options available for obtaining fibre from water hyacinth. One of the key barriers to accessing the fibre is the high moisture content. By drying the plant, without any form of prior or post processing, it is possible to use the stem as a single item in, for example, weaving mats and basket making. In such a situation the root and leaf portion of the plant would be separated out and would be available for alternative use.

When the fresh plant is mechanically processed, by grinding or crushing, the resultant slurry will be more readily separable into solid and liquid fractions. In this situation the solid is largely composed of fibrous material whereas the liquid contains the soluble organics, as well as other small particle organic solids. The waste product from this process, should it be employed to concentrate the fibre, will thus be the leaf and root portion, as well as an organic liquid.

Table 4.5 Composition and fibre dimensions of some typical vegetable raw materials.(Ghosh, 1983)

Raw material or type of fibres	Proximate analysis (% dry weight)			Average dimensions	
	Ash (%)	Lignin (%)	Cellulose (%)	Length (mm)	Diam (microns)
Water hyacinth	12-18.4	6-10	28-35	1.6	5.5
Straw	15-18	12	32	1.1	16
Bagasse	2-6	18-21	32-41	1.4	18
Bamboo	2-4	20-32	30-40	1.4-3.8	9-22
Cotton	-	-	92-97	18	20
Jute	-	12	57	2	22
Temperate softwood	1.0	26-30	40-45	-	-
Indian softwood	1.0	28-30	39-46	2.7-3.6	27-52
Temperate coniferous hardwood	1.0	18-25	38-49	-	-
Indian hardwood	0.4-1.8	21-28	35-45	0.7-1.8	9-44

The final option for separation of the fibre from the plant is by chemical treatment. As highlighted in Table 4.3 above, where a 1% caustic solution was employed, the solubility of the organics increases from less than 20% to approximately 45%. In this case the waste products will be the leaf and root portion, as well as an organic liquid containing chemicals.

Table 4.6 *Fibre dimensions (Ghosh, 1983)**

Characteristics	Minimum	Maximum	Average
Fibre length (mm)	0.66	2.53	1.604
Fibre diameter (microns)	1	20	5.5

* *For the determination of fibre length in this study, the stem was chopped and digested, bleached and washed until it was reduced to a white pulp, composed of cellulose fibres, free from other matters such as lignin and non-cellulosic constituents.*

Taking fibre as the prime product, which will be taken from the stem, and viewing the waste streams of each treatment option as a potential part of the resource, leads to the conclusion that mechanically processing the stem will provide the greatest excess. (table 4.7) The dried leaf and root portion from the drying option will be of little use, and certainly not for anaerobic digestion. The chemically treated juice will, likewise have limited usefulness, being too alkaline for easy digestion.

Table 4.7 *Process options to produce fibre from water hyacinth with emphasis on the waste stream*

	Process options	Waste stream
1.	Drying	leaves and roots
2.	Mechanically treat	leaves, roots and juice
3.	Chemically treat	leaves, roots and chemically treated juice

In the application here under review, where energy is a principle output, any fibre production can be considered only as a front end option. It is both necessary to separate the fibres from water and to carry this out prior to the anaerobic digestion process since fibres themselves contain cellulose which would tend to be decomposed within an anaerobic digester.

Fibre from water hyacinth has many applications. The one that has received the most attention is the production of paper and board. The cellulosic fibre component of water hyacinth is used to bind the non-fibrous elements. Fibre is also commercially used in the production of matting and handicraft goods. (See para.1.4.2)

Paper and board The use of water hyacinth as a source of fibre for paper and board making has met with mixed results. Exhaustive attempts at the University of Florida, for example, to make paper using various pulping conditions were reportedly a failure (Nolan, 1974). The failure was ascribed to moisture clinging to the fibre with the result that the pulp could not be drained or dewatered in modern high speed paper machines (Nasa, 1976). Research workers at the University of California, after extensive testing, similarly expressed their complete disappointment with the material as a source of paper pulp (Yaduraj, 1979).

The whole plant cannot be used in pulp manufacture as the dried leaves are brittle. Paper made from the whole plant was found to be dirty, brittle, gritty and with high shrinkage characteristics due to unequal tension of fibres and also the interference of silicious particles. The pulp gave most satisfactory results if the stem was used alone for intermediate quality paper and board (Azam, 1941). It has been reported that paper made with leaves alone lacks the strength properties needed for even packaging purposes (Zerrudo, 1979).

In water hyacinth board manufactured in Bangladesh, fibrous strands can be clearly seen and have a length of up to two centimetres. Greaseproof paper produced from water hyacinth pulp produces a material of finer quality. Water hyacinth derived paper and board, using only stems, has been determined to be of such poor quality that it becomes unsalable unless a substantial component of recycled paper is added to the water hyacinth pulp (Haider, 1987).

At the University of Florida, alkaline pulps were found to give the highest strength and bisulphite pulps to give the lowest strength properties in blends with pine kraft pulp. The tear factor decreased and the breaking length increased as the proportion of the water hyacinth pulp in the blend was increased. The burst factor increased (representing an improvement in quality) with increasing percentages of water hyacinth pulp in the blends. Kraft pulp gave the highest burst factor and bisulphite pulp gave the lowest burst factor (Nolan, 1974).

In work completed in Bangladesh and India as part of the Commonwealth Science Council's research programme, (CSC,1983) the reported fibre length and strength characteristics indicate that, with the partial addition of other feedstocks, such as waste paper, good quality papers can be made from water hyacinth, despite the negative reports from the University of Florida. Although the tear factor and folding endurance are lower, the tensile and the bursting strengths are comparable with papers made from some conventional raw materials. (Table 4.8)

Table 4.8 *Test results of paper made from bleached and unbleached pulp from various raw materials.*

Stock composition	*Basis wt. (g/m²)*	*Bulk density (ml/g)*	*Breaking length (m)*	*Burst factor**	*Tear factor**	*Folding factor (Double fold)*
Bleached water hyacinth	60.1	1.30	3710	20	33	3
Bleached rice straw	60.0	1.32	2110	10	30	2
Bleached bagasse	60.2	1.45	4250	29	57	12
Bleached bamboo	60.0	1.33	4115	36	90	85
Unblec'd water hyacinth	59.8	1.55	3778	21	30	16
Unblec'd rice straw	60.0	1.52	2360	11	32	3
Unblec'd bagasse	60.1	1.48	5585	40	47	36
Unblec'd bamboo	60.0	1.35	6220	40	84	125

* *Higher values indicate better quality*

A major drawback of water hyacinth pulp is its easy hydration in beating and its slow drainage properties, making it difficult to use in high speed paper making machines. This disadvantage can be taken advantage of for making greaseproof paper. Greaseproof paper made from water hyacinth pulp is made at high freeness from very hydrated stock and possesses certain desirable properties, such as high sheet density, high transparency and resistance to the passage of oil or grease. (Table 4.9)

It is a realistic proposition that water hyacinth could be used in large quantities for making medium quality paper and boards as well as speciality papers, such as greaseproof paper and photographic album paper, where very good strength properties are not essential. The manufacture of bond and other high quality papers is not economical due to low yield of the water hyacinth pulp.

Table 4.9 *Test results of greaseproof paper made from water hyacinth.(Ghosh, 1983)*

Measured parameter	*Result*	*Comments*
Basis weight (gsm)	*45.0*	
Bulk density (ml/g)	*0.75*	
Breaking length (m)	*5080*	*good*
Burst factor	*49*	*satisfactory*
Tear factor	*26*	
Folding endurance (double folds)	*12*	*poor*
Blister test	*very good*	
Transudation period (secs)	*1800*	

Fibre reinforced cement boards A further possible use of water hyacinth fibres is in the manufacture of cement boards. The addition of fibrous material reinforces cement products, improves their tensile strength and forms a continuous phase in a cement base. Thin sheets made with Portland cement alone are too brittle and rigid. The replacement of chrysotile asbestos by other fibrous material has become an imperative, not only due to the non-availability and ever increasing price of suitable asbestos fibres but also because of the well known associated health hazards. (Table 4.10)

Potting fibre (peat substitute) The use of the fibres from water hyacinth also offers potential for peat production. Peat adds nutrients to the soil, assists with holding water, has a structure to it which provides structure to the soil but is not excessively rigid so that new roots are not restricted. There exists the possibility of a major new market for this product as a horticultural fibre and such would be worthy of further investigation.

From the above it can be seen that, where potential has been investigated, there are significant opportunities for commercial utilisation of the fibre content from water hyacinth. The objective, however, remains to combine this potential with other products in order to maximise the potential social value of the plant.

Table 4.10 Physical characteristics of water hyacinth pulp-cement board in accordance with Indian Standard Specification. (IS 2098-1964) (Ghosh,1983)

Parameters	Indian Standard Specification for asbestos-cement board	Results of standard laboratory samples with water hyacinth
Breaking load, kg	Class A : 15-20 kg Class B : 10-15 kg	15 - 20.5 10 - 15
Thickness, mm	Class A : 6.5 ± 0.5 Class B : 5.0 ± 0.5	6.5 - 6.8 5.0 - 5.5
Density, g/sq.cm	Compressed = 1.6 Uncompressed = 1.2	1.35 - 1.40 -
Water absorption, %	40	30 - 32.8

4.2.2 Fertiliser

As with other aspects of water hyacinth utilisation, the possibility of using the plant as a source of nutrients for soil enrichment has been considered almost since its arrival, many years ago, in various different countries. Evart, writing about water hyacinth in Victorian times, said: "The water hyacinth has been used as a manure, but is very bulky and rots quickly, so that it only has a slight and temporary value in adding humus to the soil". In 1941 Bengali farmers were encouraged by officials from the British Raj to turn the water hyacinth into a composted manure. Analysis of random samples showed a nitrogen percentage of 1.12 on a dry basis. The Esholt sewage works in Bradford, England, experimented in 1947 with water hyacinth as method of water treatment. The plant covered 20 square yards from a dozen plants in two months. It was found to tolerate a pH of 6.5. It was easy to harvest and rotted easily (Dymond, 1948). More recently, the commercial processing of water hyacinth compost has been reported from Sri Lanka and the USA (National Academy of Sciences, 1976).

Table 4.11 highlights the choices available for processing water hyacinth for use as a fertiliser and makes the point that the value of the output increases with an increase of the cost of the process. The cross-over point for benefit versus cost will vary with each particular locality. The possibility of steeping water hyacinth is included here although no methodical collection of data has been made with regard to this process option.

Table 4.11 *Process options to produce fertiliser from water hyacinth with emphasis on the waste stream.*

Process	*Form of output*	*Relative value*	*Waste stream*
Mulching	*solid (mulch)*	*low*	*none*
Composting	*solid (compost)*	*low*	*none*
Drying and burning	*solid (ash)*	*medium*	*none*
Steeping	*liquid*	*medium*	*possibly fibre*
Anaerobic digestion			
whole plant feed	*slurry*	*high*	*gas*
juiced plant feed	*slurry*	*high*	*fibre, gas*

The most basic use of water hyacinth as a fertiliser is in the form of a mulch. Besides supplying nutrients, mulch also improves the soil structure, maintains soil moisture through reduced evaporation, reduces erosion, allows a temperature balance in the soil and suppresses weed growth. Through the repeated use of mulch, the upper soil becomes more permeable and the water holding capacity (field capacity) is improved due to the higher humus content (Anon, 1966) A layer of fresh water hyacinth on the soil surface increases the soil water content with increasing amounts of mulch (Abdalla, 1969). This ensues from the direct water supply out of the plants into the upper soil zones.

Water hyacinth mulch that is dug in has been found to be better than dug in water hyacinth compost and surface spread compost. This is measured by the hydraulic field capacity and the period of time to the wilting point of the growing crops (Philipp, 1983).

The nitrogen and phosphorous levels in the plant correlate with the content of the nutrients in the growth medium (Noris, 1971; Boyd,1975). An enhanced magnesium uptake has been reported, resulting from an increase in NH_4 ions. Soils treated with water hyacinth increase their C^-, N^-, P^-, K^- ,Ca^+, Mg^+, Zn^+, Mn^+ and Cl^- content, as well as their ion exchange capacity (Moulder, 1956). Exchangeable aluminium was found to decrease with water hyacinth treatments whereas the content of N', Ca' and Mg' was found to increase significantly. This was put down to the increases in ion exchange-capacity and pH (Parra, 1974). The C:N ratio has also been observed to increase in soil after treatment with water hyacinth. Normal soils have a ratio of 9-12:1. After water hyacinth additions this was recorded to have increased to 25-30:1, ie it becomes less fertile.

Work in Indonesia assessed the performance of water hyacinth mulch with soybeans, maize and sweet potato. All the crops and varieties given water hyacinth mulch yielded more than those from control plots. Generally, the yield increases with application of 60 t/ha were not much higher than with 30 t/ha. The application of water hyacinth mulch was only economic when the cost of harvesting water hyacinth was not taken into account (Sluyters, 1979).

In the USA fresh water hyacinth was mixed with fine sand and then added to soil after four weeks. All plots given a water hyacinth treatment showed a clear yield increase over the control plots. The optimal application recommended was 27 t/ha dry weight (Parra, 1976).

Despite the reports of success that are available in the literature, there are a equal number of reports of qualified success and even failure. It would appear that care must be exercised in determining to which crops water hyacinth fertilisers may be added and in what quantities. With wheat, for example, an insufficient magnesium supply is reported when the soil contains high levels of potassium as a result of water hyacinth additions (Ferrari, 1955).

A comparative study of water hyacinth compost on tomatoes and okra found the water hyacinth derived fertiliser was poor when compared to compost from other aquatic weeds. The water hyacinth compost performed less well than non-fertilised plots. (Table 4.12)

As can be seen in Table 4.13, onions, carrots and beans (biomass) increase yield with any form of water hyacinth fertilisation. Zucchinis only reacted positively when treated with compost. With mulch the reaction was negative. Okra reacted negatively to any form of water hyacinth treatment. There are indications that a yield depression may have resulted from water hyacinth treatment of tomatoes and cucumbers. Layers of water hyacinth compost and mulch reduced fruit and seed yield but increased overall biomass yield.

No consistently positive yield increases were found with the crops grown. It is suspected that the naturally high salt content of the soil in Sudan, where this study was carried out, was increased to a level that may have suppressed yields by the salt content of the water hyacinth treatments. As well as the general increase in the salts, the factor of the type of salt is relevant. Na_2CO_3 and $NaHCO_3$ are the most toxic in this respect followed by chlorides and sulphates of sodium, magnesium and potassium (Jantzky, 1957). This combined with the effect of unbalanced ionic solutions is believed to be responsible for the depressed yields obtained.

Table 4.12 Comparison of the different types of compost on fruit number and fruit weight of tomatoes (T) and okra (O). (Singh, 1962)

Compost type	Fruit numbers per plot		Fruit weight per plot		Performance ranking order	
Cowdung+soil+..	T	O	T	O	T	O
Pistia stratiotis	114	362	9.7	4.9	2	1
Ottelia alimoides	119	231	9.1	2.4	3	3
Eichhornia crassipes	116	181	6.2	2.0	6	5
Hydrilla verticillata	108	157	8.3	1.3	5	6
Cowdung	122	237	9.9	2.5	1	2
Control (No treatment)	126	234	8.6	2.2	4	4

Table 4.13 *Yields of different crops treated with organic water hyacinth fertiliser. (Philipp, 1983)*

Crop type	Control	Yield variation (% compared with control)		
	(t/ha)	Compost Test 1	Compost Test 2	Mulch
Tomatoes	0.861	- 17.5	- 23.6	- 32.1
Onions	6.875	+ 22.8	+ 14.4	+ 22.0
Okra	1.316	- 5.3	- 17.5	- 60.3
Carrots	6.190	+ 61.7	+ 33.7	+ 15.2
Cucumbers (t/ha)	1.129	- 7.9	- 29.6	- 9.0
Cumbers (Nos/ha)	8699	- 4.6	- 25.3	- 11.5
Zucchinis	4.223	+ 60.8	+ 12.8	- 22.4
Beans (fruit yield)	1.080	+ 10.2	- 15.7	- 16.7
Beans (biomass yield)	4.280	+ 60.0	+ 7.7	+ 41.1

The depression of tomatoes, which are relatively salt tolerant, may have been due to the increased level of attack from white fly, believed to have been attracted by the localised plant micro-climate resulting from the use of water hyacinth mulch and compost.

Various methods have been employed for producing compost from water hyacinth. In the Indore technique, water hyacinth is piled up into small heaps, approximately 3m x 3m x 1.8m high, and in layers of 30 cm alternating with cow dung, sewage sludge or ready-for-use compost. The cow dung was found to be the most effective seed for the composting process. The entire process takes 3-5 months to complete (Basak, 1948). A similar technique, employing fresh cow dung, was found to be better than water hyacinth alone or water hyacinth with inorganic fertiliser. In this experiment the pile was turned twice and the process was complete within three months. The best growth promotion of tomatoes was obtained with water hyacinth plus cow dung. In the Sudan, the compost was prepared from freshly chopped water hyacinth, cow dung and soil. The layered piles were skewered with bamboo poles and these were turned in circles on a daily basis to facilitate aerobic decomposition. The piles were turned on a weekly basis. After two months the compost was ready (Philipp, 1983).

In another method, water hyacinth is dried in the sun prior to being piled up with alternating layers of wood ash and soil in a circular bamboo construction (Watson, 1947). The use of water hyacinth with thomas-slag (Dhar, 1963) and with superphosphate (Gratch, 1965) has also been investigated.

Ash has been considered as a fertiliser, despite the loss of the organic content and nitrogen in the process of producing ash, because the remaining nutrients are in a concentrated form (Finlow, 1917). Field experiments showed a yield increase of 25% in jute with additions of 105 kg/ha K_2O as water hyacinth ash. The high levels of SiO_2 found in small plants means that these cannot be recommended for use as a fertiliser. The ash has a high potassium content and the Ca and P content may encourage plant growth. (Table 4.14, Table 4.15 and Table 4.16)

Potassium extraction has been investigated by means of hot water solubility. About 98% of the K_2O can be extracted by this means. The extracted portion of P_2O_5 and KCl was also found to be above 95%. The salts are produced by evaporation (Day, 1918). It is reported that this salt residue is consumed as a food by some South American Indians (Schultz, 1962).

The fertiliser produced from the anaerobic digestion of water hyacinth is enriched in N, P and K. Where the water hyacinth is grown on a high nutrient water base, such as that of a sewage farm, the quality of the fertiliser is dramatically increased. The use of a liquid fertiliser is one that will be widely acceptable. In western societies, the application of sewage sludge direct to the land was readily accepted until it was discovered that high levels of cadmium, lead, mercury and nickel were found in the sewage sludge. The problem here is that by fertilising fields with sewage sludge containing these elements they are introduced into the food chain and concentrated in human beings. This problem will not exist in fertiliser derived from water hyacinth except in those locations where the water hyacinth is grown on water containing effluent from chemical processes. Where this is the case the fertiliser that would be available should not be used for growth of crops to be consumed in the human food chain, but could be used for other crops such as timber, lawns and ornamental gardens.

Table 4.14 *Nutrient content of ash from water hyacinth of different sizes. (Finlow, 1917)*

Nutrient	*Big plants*	*Small plants*
Ash as % dry matter	*30.6*	*29.8*
SiO_2 as % ash	*20.7*	*49.4*
K_2O as % ash	*34.2*	*11.4*
P_2O_5 as % ash	*8.2*	*1.4*
CaO as % ash	*8.4*	*7.8*
Cl as % ash	*20.4*	*5.7*

A study was carried out in 1945 to determine the rate with which water hyacinth takes up various salts. The following components were added to the growth medium of water hyacinth:

KNO_3	-	0.25 gms/l
$MgSO_4$	-	0.25 gms/l
$Ca(NO_3)_2$	-	1.00 gms/l
H_2KPO_4	-	0.25 gms/l
$FePO_4$	-	0.25 gms/l

The period of growth was two weeks and the results as presented in Table 4.15 were obtained.

The silica dropped as a result of displacement. The nitrogen rose from 1.42 to 2.23% in two weeks. There appears to be a rapid curve of absorption for seven days, after which a state of equilibrium between growth and absorption is attained.

Table 4.15 *Analysis of water hyacinth before and after addition of salts to growth medium (Dymond, 1948)*

Compound	Before addition of salts	After two weeks
Water content %	94.1	95.5
Dry matter %	5.9	4.5
Nitrogen % dry wt	1.42	2.23
Ash % dry wt	34.00	29.30
ASH CONSTITUENTS(%)		
Total silica	44.74	23.92
Chlorine	6.04	9.58
Iron and alumina	23.00	30.40
Sulphates	2.46	2.81
Lime	6.80	8.00
Magnesia	4.64	5.06
Phosphoric oxide	2.00	8.00
Potash	7.36	11.62
Undetermined	2.96	0.61

It was deduced, as a result of the work by Dymond (1948), that one acre will absorb 2.35 tons of ammonium sulphite in one hour. This work came to the conclusion that a city of 200,000 people would require approximately 900 cropping acres of water hyacinth, to absorb its urine production and convert it to fertiliser, which would yield 1400 tons of organic nitrogen per annum. The potential commercial value would be increased if the phosphoric oxide and potash were allowed for in the calculation. This assessment is based upon only the urine effluent from the population and takes no account of the solid wastes that accompany it.

The C:N ratio of water hyacinth is ideal for both anaerobic and aerobic decomposition, being in the range 26 - 35:1. When composting, to guarantee a quick decomposition, good aeration is necessary. The requirement is calculated to be 1.44 m^3 air/kg dry organic matter. The optimal water content for composting is 50%. Above 50% there is the possibility that anaerobic decomposition may commence and below this the process may be retarded. As newly harvested water hyacinth contains 95% water it must be partly dried before composting. The composting process is improved when the plant is chopped up to provide a larger surface area (Poincelot, 1972).

Where water hyacinth mulch or compost is applied to soil, the presence of weeds, although initially suppressed, has later been found to increase and to be difficult to control with hoeing, as a result of the mulch and compost in the soil. Results from such work suggest that applications of pesticides and herbicides may be necessary to control increased attack from white fly, mildew and nutgrass following on from the use of water hyacinth mulch and compost.

Table 4.16 Analysis of water hyacinth ash. (Dymond, 1948)

Compound	Sample from a pool deficient in plant food	Sample from a slow running river in Zululand
Total silica	58.02	39.40
Chlorine	3.55	9.23
Iron and alumina	19.35	17.00
Sulphates	2.40	2.57
Lime	6.75	8.50
Magnesia	2.20	5.61
Phosphoric oxide	0.86	4.00
Potash	4.81	11.20
Undetermined	2.06	2.49

Similarly, the use of ash for ground nut fertilisation was found to be unsatisfactory. Poor rainfall during a trial in the Sudan was believed to be the key ingredient in reduced yields over the three year experimental period. The high levels of Ca and Mg in water hyacinth ash applied to the fields where groundnuts were planted are believed to have led to an overdose and the final recommendation was for a maximum application of 2 t/ha (Philipp, 1983).

In summary, the use of water hyacinth as a feedstock for the formation of soil conditioners and fertilisers is one that has qualified potential. It is clear from the literature that care must be taken in applying any particular form of fertiliser to specific crops as there may be an adverse effect and this would be highly undesirable. On the other hand, where the plant has been successfully employed it has demonstrated the potential that it could have on a larger scale.

4.2.3 Protein and fodder

Protein isolates from leaves and grasses have been used as a useful supplement in human diets (Albanese, 1967). Leaves and grasses provide more protein than other foodstuffs of vegetable origin. The manufacture of leaf proteins for highly populated countries might be economical. In this respect, water hyacinth leaves (and perhaps stems) might be exploited for human food protein. Despite this potential, there remains considerable development work to ascertain exactly how this may be achieved and how beneficial it might prove to be.

The possibility of using water hyacinth as a fodder for ruminants has been studied many times (Chatterjee, 1938; Hossain, 1959; Little, 1968; Soewardi, 1974; Osman, 1975; National Academy of Sciences, 1976; Pieterse, 1978; etc.). The general conclusion is that feeding animals with water hyacinth alone is not possible. The use of water hyacinth as one of several components in a diet, as opposed to the only component, has achieved greater success. The high KCl content is usually considered to be the source of the unpalatability of water hyacinth fodder. Feeding sheep with water hyacinth alone caused heavy weight loss, diarrhoea and death in a study carried out in the Sudan (Osman, 1975). Where sheep were fed water hyacinth, in combination with a feed concentrate, weight increases were measured. Feeding water hyacinth to pigs has generally been considered to be more successful and is practised in certain parts of the world (Hora, 1951; Villadolid, 1953; Pirie, 1967; Mahmud, 1967; Combs, 1973; Mahendranathan, 1970; Devendra, 1976; Susiawanigrini, 1977). Water hyacinth is used as a fodder for cattle, pigs and buffalo in Bangladesh, India, South-East Asia and China. Several workers have reported the use of the water hyacinth in pig and fish feed (Hora, 1951; Le Mare, 1952; Hue, 1958; Choy, 1958; Ark, 1959; Fisher, 1963). The feeding of fish with water hyacinth compost, as well as water hyacinth greenmeal, has been found to produce positive effects on certain types of fish (Mitra, 1971; Liang, 1971).

One of the many investigations of water hyacinth carried out by Wolverton was an examination of its nutritional value to cattle. Whilst there was considerable variation in the nutritional components, his overall finding was that it was equivalent to the generally accepted land fodder plants (Wolverton, 1978). However, it is possible, where water hyacinth has been used for water purification, that it may have become toxic.

Feeding water hyacinth preparations to poultry has also been found to be relatively successful (Smetana, 1967; Ross, 1971; Susiawanigrini, 1977; Thohari, 1979). The relatively high carotine content (13,100 IU/100g feed) of water hyacinth green meal is an important factor in this success. Geese, chicken and ducks have all taken part in this research.

The possibility of using water hyacinth to form silage has similarly been the subject of considerable attention (Bagnall, 1974; Loosli, 1954; Agrupis, 1953; Baldwin, 1973,1974,1975; Byron, 1975, Gohl, 1975, etc.). Water hyacinth silage feeding value, as with its use as a fodder, is generally considered to be poor.

Table 4.17 *Protein and fodder : process options for production from water hyacinth with emphasis upon the waste stream.*

Process	*Relative value of product*	*Waste stream*
Grazing	*low*	*none*
Fodder	*medium*	*roots*
Silage	*medium*	*roots*
Greenmeal	*medium*	*roots*
Leaf protein production (curd)	*high*	*fibrous mat, stems and roots, whey (sugars)*

The amino acid composition (based on FAO data) is relatively good. The values of the essential amino acids valin and methionin are, however, too low (Taylor, 1968). The amino acid composition is important for utilising the water hyacinth as fodder and indicates its protein value. The utilisation of digestible protein is limited should there be low levels of amino acids (Menke, 1980). Only Cystein and Methionin are below the FAO standards (Block, 1956). This means that water hyacinth protein is of high value and is comparable to milk protein. It has a high nutrient content in comparison to grass and alfalfa forage (Knipling, 1970). Unfortunately, high levels of acetic acid, resulting from the silage fermenting process, caused a penetrant smell and reduced palatability in silage fed to sheep in the Sudan (Philipp, 1983). A great loss in nitrogen was also evident in the silage preparation technique, resulting in a reduction in protein, probably as a result of an obligate anaerobic putrefactive bacteria.

Trials in Fiji were conducted with pigs, goats, rabbits and ducks. These were fed with varying concentrations of water hyacinth. Preparation in this case was minimal. The bulk of the water hyacinth remained green and succulent for several days during which time 50% of the moisture was lost. After this time, the pile of water hyacinth tended to rot and become unacceptable as an animal food. Water hyacinth alone putrefies very rapidly and the additional preserving agents such as molasses or other carbohydrates are necessary to produce satisfactory silage (Bagnall, 1969; Baldwin, 1974).

In yet another trial, water hyacinth leaf protein concentrate added to the diets of chicks was found to result in a *lower* protein feed. The chicks on the control diet performed better in growth trials (Kashem, 1983).

Table 4.18 *Amino acid composition of water hyacinth from three sources.*

Amino acids	Philipp, 1983 (g/100g crude protein)	Taylor, 1971 (g/100g crude protein)	Taylor, 1968 (g/100g crude protein)
Cys	1.76	0.30	–
Asp	11.29	10.20	–
Met	1.56	1.80	0.72
Thr	5.09	5.00	4.32
Ser	5.23	4.80	–
Glu	11.87	9.80	–
Pro	–	4.80	–
Gly	5.94	6.40	–
Ala	6.72	7.10	–
Val	6.21	6.00	0.27
Ile	4.88	5.20	4.32
Leu	8.81	9.10	7.20
Tyr	3.60	3.90	--
Phe	5.69	5.50	4.72
NH_3	2.73	--	--
Lys	6.06	6.20	5.34
His	2.32	2.30	--
Arg	5.71	5.20	--

The production of protein from leaf juice is one that is fraught with difficulty. The timing of the collection of the protein and its extraction needs to be subject to careful control and, where such care is not available, the system will not function correctly. Where leaf protein is made with care, however, it may be considered to have good nutritive value. It is noted that the most valuable nutritional benefit may be obtained by consuming the protein soon after production. Where the protein is stored for more than a few days the Beta-Carotene content is lost (Gooding, 1991).

The protein obtained from water hyacinth can be classified for its quality, according to its analytical values, between that of egg protein (taken as 100%) and leguminous protein (taken as 50%) with an average of 87% (Oyakawa, 1965). The value of leaf protein concentrate is similar to soyabean meal when leaf protein concentrate of different leaves are used as a source of supplementary protein in the diets of growing chicks (Duckworth, 1961). Water hyacinth also compares well with Napier and Guinea grasses and is superior to rice straw in digestible nutrients (CSIR, 1951). The crude protein has been given various values on a dry weight basis; between 4.7 and 9.2% (Taylor, 1968); between 5.6 and 12.1% (Osman, 1975); between 12 and 19.8% (Boyd, 1968 & 1974).

Table 4.19 *Concentration of proteins, carbohydrates (total) and sugars during the course of anaerobic fermentation at 32°C. (Ghole, 1983)*

Measured variable	Day 0	Day 2	Day 5	Day 9	Day 20
Protein concentration (g/l)	0.185	-	0.085	0.085	0.085
Total carbohydrates (g/l)	0.88	0.70	0.625	0.062	0.015
Fermentable sugar (g/l)	0.076	-	0.021	0.005	0.0

In the case of protein extraction, it is likely that if this is removed prior to the anaerobic digestion process, the protein that would otherwise be available for growth of the bacteria will be absent. It may be that this will reduce the overall efficiency of the anaerobic digestion process. The whey, or fermentable sugars, that are a byproduct of the leaf protein production process might be considered for use as part of the feedstock to a system which used the root and stem for anaerobic digestion.

As is demonstrated in Table 4.19, the reduction in protein during the process of anaerobic digestion would make protein collection a front end process only. It is possible that leaf protein harvesting could be combined with anaerobic digestion of the remnant parts of the plant. Additional work is required in this area to fully assess the relevant factors involved.

In summary, as with fibre and fertiliser production and use, the food value of water hyacinth is not an unqualified opportunity. Care must be taken in its use and it should never be used as a solitary component in a diet.

4.2.4 Summary of potential and constraints

Fibre

The potential market for water hyacinth paper and board would be significant, if manufactured with proper quality controls and marketed in an effective manner. Water hyacinth greaseproof paper, for example, would compete with papers of this quality manufactured from other feedstocks. Where water hyacinth fibre for paper and board production may be available as a waste product from an energy producing process, and thus essentially free, its competitive position would be greatly strengthened. As with any new product there would be a period of establishment but, to some extent, this has already commenced. The principle constraint to the use of water hyacinth pulp on the world market is the twin requirement for reliability of supply and predictability of quality. In the context of Bangladesh, both of these prerequisites would be hard to satisfy without significant investment in management and product controls.

The possibility of methane from water hyacinth providing energy for the cooking requirement of pulp production is one that merits further attention. On a broad basis, a cooking time of two hours at 130°C for 1 kilogramme of crushed water hyacinth stems would require approximately 2 - 3 MJ of heat. One kilogramme of water hyacinth can produce approximately 250 litres of methane which is equivalent to 8.75 MJ of LCV heat. With a reasonable level of insulation and boiler efficiency it is possible that the whole process could be self sustaining in energy terms. The energy cost of harvesting and crushing the water hyacinth would affect the overall equation, as would the exact temperatures and times required for the pulp production process.

The actual properties of the finished product relegate it to a low quality or speciality product area. Paper produced from water hyacinth alone would appear not to be viable and it will be necessary to allow for the addition of other constituents.

The use of water hyacinth stems as a large fibre for weaving and basket making is already well established in Thailand. This is a rather limited opportunity and not one which matches the waste product availability from a system designed to produce energy on a commercial scale.

Fertiliser

The use of water hyacinth for fertiliser production falls into a similar functional category as that for fibre. On its own it is often of dubious benefit and, sometimes, of considerable disbenefit. There are, however, opportunities where it can be commercially employed to increase crop production. Care must be exercised in making recommendations in this regard. The problem of salt overdosing, for example, together with the potential for toxic compound concentration in the plant tissues make it necessary not to view the potential as universal.

Protein

In the case of fodder and protein, the plant is again in the position of being inadequate on its own, except in certain specialised circumstances. Feeding trials have demonstrated conclusively that fed on water hyacinth alone, livestock will suffer various degrees of difficulty. In combination with other feeds the water hyacinth may be successfully utilised.

Multiple product systems

As will be discussed in the next section, the optimum benefit may be gained by combining product output from the harvested plant. Each sole product on its own has the appearance of marginal benefit but, when viewed as part of a system with multiple products the picture changes significantly.

4.3 THE RELATIONSHIP BETWEEN BIOGAS, FIBRE, FERTILISER AND PROTEIN PRODUCTION.

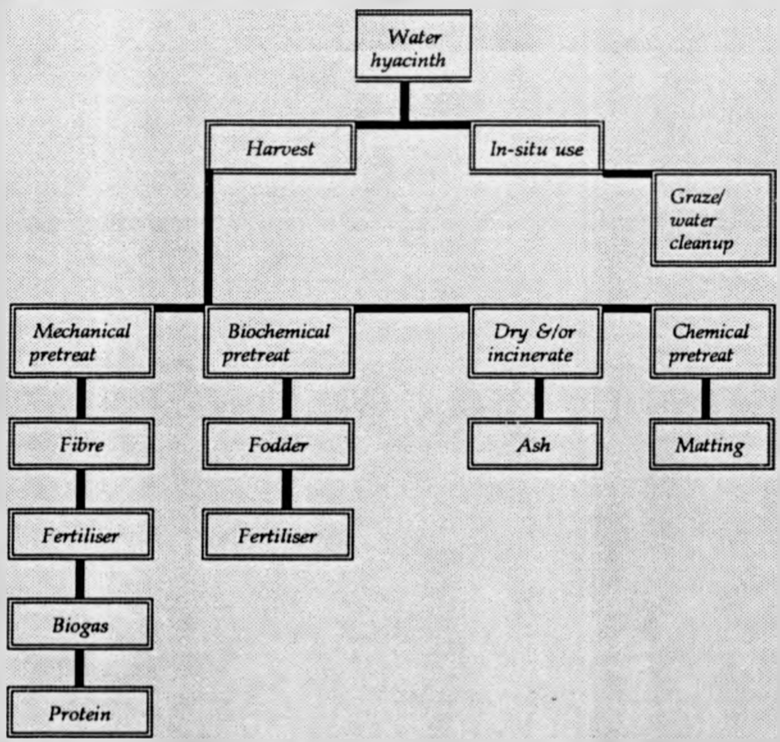
The principal product combinations are listed below:

Process option :	i	Fertiliser alone
	ii	Fibre alone
	iii	Protein alone
	iv	Fibre and fertiliser
	v	Fibre and protein
	vi	Fertiliser and gas
	vii	Fibre, fertiliser and gas

Figure 4.1 summarises the discussions in the previous sections in this chapter concerning product combinations.

As the preceding sections of this chapter have highlighted, there are many possible uses for water hyacinth. A few of these are clearly commercially viable, whereas the majority are economically marginal. It is a proposition of this thesis that in order to economically realise the resource potential of water hyacinth, it is necessary to look at combined-output systems. Further, it is also taken as a key proposition that biogas should be one of the outputs. The primary reasons for biogas being identified as a necessary output are that it does not exclude other potentially viable outputs and yet energy products command a high value. As Figure 4.1 highlights, the extraction of fibre, fertiliser, gas and possibly even leaf protein, may be complementary processes. Fibre has various potential applications, which do not require the soluble organics. Improved separation of fibre at the commencement of any system would improve the quality of the fibre and maximise the residual organics that would be available for the remaining processes. Likewise fertiliser quality will not be diminished by passage through an anaerobic digester. Indeed, a liquid fertiliser would have potential for application in situations where the bulk weight of unprocessed water hyacinth would not be suitable. The preferred production option is fibre, fertiliser and gas (No.(vii) above).

Figure 4.1 *Principal pathways for water hyacinth utilisation currently under investigation.*



There remains the possibility in the case of protein, that this may be extracted from the leaves in such a manner as to prevent the overall system output from being reduced significantly. The leaf contributes approximately 12% by weight of the whole plant, and following extraction of the protein from the leaf, there remains the sugar rich whey which can be introduced to the anaerobic digester for gas production. In the case of high-rate anaerobic digesters, one of the factors which threatens success is bacterial loss. Protein will be required during the initial growth of the bacteria, but once the plant bacterial colony is established, there is reason to believe that the protein requirement may be significantly reduced. This being the case, extracting the leaf protein, whilst retaining protein within the root and stem, would in all probability not affect the gas production significantly.

Maximising the combined outputs entails the increased technical sophistication of the overall system. A low technology approach, such as mulching, will have limited scope for commercialisation.
Biogas has two principle components. The first is methane with its energy component being of primary interest. However, the carbon dioxide component may be of commercial significance too. Carbon dioxide is used widely as an industrial gas for food processing and other such applications. Industrial carbon dioxide may be obtained from various sources, such as off-gases from the fermentation of beer or the combustion of cheap oil, followed by the separation of the exhaust gases to purify the carbon dioxide. There may be scope for taking biogas produced from water hyacinth and burning it to obtain a high yield of CO_2. This possibility will be viewed later in the text.

For realisation of water hyacinth as a resource, it is apparent that the combination of fibre, fertiliser and biogas production presents the most promising possibility. The current thesis will concentrate upon this process combination. It is acknowledged, however, that other routes have the potential for commercial viability and these should be looked at separately.

4.4 CONTINUOUS LARGE-SCALE PRODUCTION

While it is possible to treat water hyacinth by means of batch processes, continuous processes are generally preferable. However, these latter face problems that are discussed below. Whichever product combination is considered, assuming it includes biogas, the commercial economics strongly favour continuous production. Anaerobic digesters do not operate in a manner which facilitate diurnal flow rate changes and the capital invested may be fully employed by running any plant twenty-four hours per day.

4.4.1 Feedstock availability

This leads on to certain key considerations. For example, with any type of continuous digester, the intervals between feeds must not exceed (say) 20% of the hydraulic retention time (HRT). With high rate digesters there is an essential requirement for a continuous feed. The feedstock may, however, be varied slowly over time and this may be necessary to match the seasonal variations in feedstock availability. The rates of such allowable variations will vary with the digester type. As will be discussed more fully below, in many countries the growth rate of water hyacinth varies strongly with the seasons. Long term buffering may be available from the stock of growing plants in the pond but the key method of adapting the system to feedstock availability will be to match the base load availability of plants to the size and output of the system. Likewise, there may be variations in the usage patterns of the outputs.

In sizing the operational components involved in a system it is necessary to assess the available feedstock and the available demand for the products. It is unlikely to be economic to keep the plant going at less than 10% of its design capacity. In all probability, commercial realities would not permit a plant to run at such a low level of use. The unavoidable overheads involved in management, operation, maintenance and financial capital servicing would necessitate that the system run at as near maximum output for as long as possible during any one year. It is suggested that the plant be sized for (say) 60% of the maximum growth rate it would be possible to achieve and the local economics be worked up and down from this point. If it is commercially feasible, it may be possible to arrange for a variable rate of production that could range from 30-60% of capacity.

Table 4.20 *Estimated growing seasons (months) vs plant growth rate in three countries.*

Growth rate as % of max	*Bangladesh*	*Florida*	*Thailand*
50 - 100%	*7*	*5*	*8*
10 - 50%	*3*	*2*	*2*
< 10%	*2*	*5*	*2*

The above rationale results in four operational strategies. Strategy one will be a constant throughput at (say) 60% of peak growth rate throughout the year. Strategy two will be a variable throughput at (say) 30 - 60% of peak growth rate throughout the year. Strategy three will be a constant throughput at (say) 60% of peak growth rate for a defined period but not the full year. Strategy four will be a variable throughput at (say) 30 - 60% of peak growth rate, again, for a defined period but not the full year.

In Bangladesh and Thailand strategies one and two could be applied whereas, by contrast, in Florida it would be possible to obtain (say) 7 months production with strategies three and possibly eight months with strategy four. (Table 4.20) In other locations where temperature rarely drops below 20°C, it will be possible to use either strategies one or two. The periods of low growth would need to be buffered out by the size of the growth ponds. In countries where significant periods of temperatures below 20°C occur, such as in Florida, either strategy three or four would be available and the period of production would depend upon the climate.

Table 4.21 *Seasonal variations in plant composition (% dry wt) in Florida. (Boyd, 1970)*

Time sample taken	*Dry matter*	*Crude protein*	*Ether extract*	*Cellulose*
April	*5.0*	*22.0*	*5.29*	*25.7*
May	*5.0*	*23.5*	*5.60*	*26.7*
June	*8.0*	*18.2*	*3.75*	*22.8*
July	*7.3*	*15.7*	*5.11*	*21.6*
August	*7.0*	*19.4*	*3.84*	*20.4*

Coupled with the quantitative growth rate variations of the water hyacinth with seasonal climatic variations there is also a qualitative variation. This is highlighted in Table 4.21 and Table 4.22. Seasonal variations have been found for crude protein, ether extract, cellulose and dry matter (Blackburn, 1970). The nature and causes of such seasonal changes are not well documented and would require to be understood in more detail. It is probable, however, that they result primarily from variations in the nutrient make-up changes, resulting in turn from such factors as wet and dry seasons. Where there is increase rain there will be increased run-off of nutrients from the land and these will be available to the plant. The possibility of levels of insolation affecting the manner in which the plant grows should not be overlooked.

Table 4.22	*Contents of water hyacinth at Tawila, Sudan. (% dry wt) (Philipp, 1983)*

Date	Ratio of root to stem	Plant ht (cm)	Org' matr	Ash	Crude prt'n	Ether ext't	Crude fibre	PO4	Ca	Mg
Jan	0.72	50	77.2	22.8	6.7	0.45	41.0	0.27	1.63	0.72
Feb	0.76	42	74.9	25.1	5.7	0.72	47.1	0.25	1.31	0.58
Mar	1.40	40	82.5	17.5	7.6	1.28	39.2	0.20	1.59	0.73
Apr	1.32	43	77.8	22.2	6.9	1.19	45.0	0.19	1.51	0.60
May	1.95	40	63.6	36.4	4.8	0.38	61.6	0.26	1.17	0.75
Jun	1.84	52	74.6	25.6	7.2	0.42	39.8	0.21	0.97	0.72
Jul	0.63	52	56.4	43.6	4.5	0.14	57.5	0.21	3.20	0.55
Aug	1.28	35	66.5	33.5	5.5	1.05	54.5	0.28	0.81	0.80
Sept	1.23	32	71.6	28.4	7.5	0.88	50.2	0.29	3.02	0.78
Oct	1.23	42	69.6	30.4	10.0	0.59	53.4	0.30	1.87	0.67
Nov	0.68	55	73.5	26.5	6.7	0.46	45.7	0.27	1.62	0.73

Harvesting

In order to optimise the harvesting technique selected, it will be necessary to minimise the amount and rate of energy expended in collection and transport to the point of use. The ratio, kilowatts per tonne, will be of critical importance to the overall system efficiency. A system of using natural forces to concentrate the plant for harvesting will be one which will have a significant impact on this ratio. Ensuring that the point of use is the minimum feasible distance from the point of harvesting is one which will require attention. Being a fully floating aquatic plant, water hyacinth moves readily with water flow. The use of water flows to move the plant towards the point of harvesting will assist in the process of concentrating the plant for harvesting.

Continuous feed requirement

In order to operate a system on a continuous basis, it will be necessary to have available a continuous feed. In the case of a high rate digestion process this means that the feed will be input twenty four hours a day. This is a significant departure from a batch process where, typically, feed will be input once every five to ten days. It will, therefore, be necessary to continuously harvest and pre-treat feed to the digester, or to be buffering the feed in a form which enables the digester to draw feed on a steady basis. In the case of the multi-stage upflow anaerobic digester the flow rate is a critical parameter in the successful operation of the reactor. If the flow rate is increased, it is likely that the bacteria will be washed out and thereby the overall process efficiency reduced. Buffering a feed is not in itself a significant problem, if anything it may lead to an improvement in the quality of the feed in that dissolved or entrained oxygen will be either consumed or removed as the feed awaits introduction into the anaerobic digester.

4.4.2 Matching gas supply to gas consumption

Gas storage

Where gas is to be utilised for process heat generation or cleaned for use in vehicle fuels, it will be necessary to have control over the rate at which the gas is stored and used. Typically this is accomplished by means of gas holders. Peak shaving plants in western societies, installed local to peak demand and intended to buffer the peak out of the supply system, employ gas holders to balance load variations. During off peak periods the gas holder will tend to fill up and, as the peaks come and go, the gas holder will be depleted. Another method of peak shaving is cryogenic liquefaction. As the gas will be employed within a relatively short space of time, there is not a significant requirement for re-liquefaction to prevent excess losses. Cryogenically liquifying methane as a method of storage is one that may have its attractions in certain circumstances. Cryogenic liquefaction is, however, a process with an efficiency less than would be desired in a storage process. Typically, using a Phillips Stirling cryogenerator, the efficiency in terms of energy will be in the region of 70%. Where the gas is used to generate electricity, it is probable that the question of load variation will not arise should the electricity be introduced into a local network. If, however, the electricity is employed locally and is not connected into a wider reservoir of electricity production, it is likely that the peaks and troughs of the load will be significant and problematical.

Gas collection and use

With regard to gas production, the ideal situation will be for the system to have the minimum of buffering and the maximum of direct utilisation. Where the gas is drawn off from the digester and immediately used, the cost of storage will be negligible. However, it is probable that this will not be the normally encountered circumstance. Where storage is required it will be necessary to pay close attention to the cost of gas storage versus the income derived from gas sales.

Where a gas holder is employed, the gas transferred to a point of use will be vary with demand. It is a combination of operating costs and capital costs set against the value of the product gas that is stored for later use that must be assessed.

Digester operation to match load

An example of long term digester operation is the case of a domestic waste landfill site, from which biogas is being drawn for utilisation, in a western economy. Such a landfill may be viewed as a large batch reactor with a retention time typically of 30-40 years. Where a varying diurnal load requirement is encountered, the reactor volume also acts as a storage vessel. Gas may be drawn off at rates which vary to match the load.

In the case of high rate anaerobic digestion, however, the volume of the digester will be minimal in comparison to the gas storage requirement. Drawing gas off to meet the load will not be an option available to operators. The possibility, however, of increasing and decreasing the input feed to the digester to match load fluctuations is one that is worthy of further investigation. From a simple assessment, it is clear that the lead times required to accelerate and decelerate the rate of gas production will not provide for the degree of control required. With a retention time of one day should it be desirable to cease production overnight, it will be necessary to stop feeding the bacteria at some point during the course of the day. If this is not done gas production will continue through the night as organic substrate is consumed. A reduction in feed during the night will, similarly, cause a problem in the morning. Matching feed and flow rate to output gas production does, however, form an attractive possibility and a more detailed study of this would be one worth carrying through.

In pipelines

Prior to the appearance of the national gas network in the United Kingdom, gas was stored either in gas holders or in cryogenic peak shaving plant. With the advent of the national gas network it was possible to store gas in the pipeline by varying the pipeline pressure. This enabled peak shaving plants and gas holders to be removed. For this to be a realistic option the volume of the pipeline, however, must be considerable and it is unlikely that within the context of even a large scale anaerobic digester the pipeline volume will be significant in comparison to the rate of daily gas production.

Cryogenics

As has been mentioned above the possibility of using cryogenics for gas storage is one that may be worthy of further attention. Where the option is a loss of gas production, i.e. 100% inefficiency, the possibility of employing a system which enabled 70% of the gas to be retained is one that has its merits. The problem with cryogenic liquefaction of methane is that the carbon dioxide component in the biogas will need to be removed prior to liquefaction. If this is not done the carbon dioxide will freeze and block the pipelines at a temperature of approximately -40°C it will, therefore, be necessary to have a scrubbing and polishing stage prior to the cryogenic plant to remove carbon dioxide to below trace gas levels. This will all add significant cost to this option for storing gas.

Gas holders

In batch digesters with retention times of, typically, thirty to forty days, one favourite design is to employ the roof of the digester as a floating gas holder. The gas production is, therefore, balanced out with the load by storing excessive capacity within the digester itself. In the case of a high rate digester, this will not be practical. The volume of the gas holder would be significantly greater than the volume of the digester. With a thirty day retention time the volume of the gas holder is typically 20% of the digester volume. With a one day retention time, the volume of the gas holder will need to be approximately 500% the volume of the digester itself to perform a comparable buffering operation. Where maximum production is being targeted, a digester of 10 m^3 will require a gas holder of 50 m^3 to match the ratio employed in a batch digester. This is clearly not an ideal method of operating the system. The cost savings obtained by reducing the size of the digester may be lost in the cost of the storage vessel.

Compression

As with liquefaction, a significant energy input is required to compress gas to typical storage pressures of 200 bar. In the case of biogas there is also the added disincentive in that 40% of the gas being compressed is typically gas that is not required. Were compression to be considered it would therefore be desirable to remove the carbon dioxide. The major capital requirement for a storage system based on compression would be the storage vessels themselves. The cost, both capital and operational of the compressors themselves will also be significant. In order to withstand storage pressures of 200 bar, it is necessary to have very strong cylinders. Compression will reduce the storage requirement by a factor of 200. Where a storage capacity of 50 Nm^3 is required this may be reduced, therefore, to 0.25 m^3. This is equivalent to a five 50 litre water capacity storage vessels. The possibility of compression for load matching may, in some circumstances, be the most practical option available.

4.4.3 Matching fertiliser production to consumption

There are two problems that must be considered with regard to fertiliser production. The first is matching continuous production to seasonal usage, involving questions of buffering. The second is the cost of transport, which will be lower if the fertiliser is more concentrated.

Liquid containers

The problem of liquid fertiliser storage is similar to that of the transportation of water hyacinth. The high water content in comparison to the quantities of useful material provides a problem for the user. It is necessary to store and transport large volumes of liquid in order to extract the useful components. It is, therefore, desirable that the storage and transport of effluent from the anaerobic digester is maintained at the practical minimum.

Drying

The possibility of drying the effluent in order to concentrate the N P and K is one that encounters problems similar to those of drying water hyacinth to concentrate the solids. The volumes of liquid will be comparatively large and the amount of heat input to significantly reduce the water content will likewise be large. It is possible that solar energy may be employed to remove water by evaporating out excess liquid. Where this is feasible it should be used to the extent that is practical.

4.4.4 Operational considerations

Pre-treatment

In order to prepare water hyacinth for high-rate anaerobic digestion it will be necessary to slurry and press the whole plant. For the experimentation carried out within the context of this thesis the slurrying process was carried out with various instruments. A mincer was found to produce the optimum product. Mincing is itself a process which has undergone numerous historical refinements and it is, therefore, at an optimum of its current stage of development. In order to extract juice from slurried water hyacinth it is necessary to press the slurry. As part of the current research programme the pressing stage was carried out with a manual press, but it is probable that in practice it will be necessary to mechanise the pressing stage. The amount of energy expended in mechanically preparing the water hyacinth for introduction to the digester is one that must be monitored carefully. The critical ratio of energy consumed per unit of feed is one that must be optimised. There is a possibility, for example, that de-watering processes, as commonly encountered for sludge drying in the chemical industries, would perform the operation more economically than pressing. It was discovered in the course of the current experimentation that manual pressing may be effectively or ineffectively carried out depending upon the care with which the slurry is pressed. If the layers of slurry for pressing exceeded approximately 1 cm then the volumes of juice extracted were reduced and the quality of the juice was also reduced. This was particularly the case with the leaf where excessively thick layers in the press resulted in a high insoluble solids content in the juice.

4.4.5 Operation of a continuous biogas process

Continual supervision

In a large scale process where anaerobic digestion is occurring at a high rate, it will be necessary to have methods of supervising the plant on a continuous basis. It will not be adequate, for example, for the plant to pass through a period from 6 o'clock at night until 8 o'clock the next morning without receiving any attention. It may be that during the course of the night the pH will drift outside of the set range and by the time the morning comes the bacterial colonies within the digester may be destroyed. There are, however, various methods available for providing online supervision without the need for continual human supervision. Monitoring pH by means of instruments is a common requirement. Work carried out at Imperial College has demonstrated that there are other parameters which may be monitored to detect whether or not the system is operating effectively. The production of hydrogen is one such parameter that has been identified. Where hydrogen production increases, this may be taken as an indication that the quantities of formic acid are exceeding desirable limits and corrective action is required. It is, therefore, envisaged that the full instrumentation of a digester for use in such a situation will be a necessity.

Plant operation and maintenance

As with all process equipment of any complexity, it will be necessary to plan operation and maintenance. This will require technicians skilled in a number of disciplines, as well as unskilled labour for manual work such as cleaning out and repairing the digester. The question of economies of scale is one that will be brought into the equation. It is likely that, as with any system, it will not be desirable to have one large reactor producing the full output requirement from the system. Rather, the plant will be split into units of convenient capacity and output with maintenance requirements balancing the available capacity with the capacity that may be down at any one time. A system from harvesting to pre-treatment to digestion to electricity generation will be comparatively sophisticated, in terms of developing country technology, and it will be necessary to ensure that the system operation and maintenance is carefully planned.

4.5 ECONOMIC GAS PRODUCTION FROM WATER HYACINTH

In this section the number of factors that effect economic viability are discussed. The data necessary to compute such viability is identified and a number of significant ratios are defined. The system proposed for the utilisation of water hyacinth is one that contains the possibility for many alternative techniques. In each locality there will be some modification to any standard scenario for commercial exploitation. To assess such variations, a framework will be provided with which to evaluate options. The framework will define the various inputs and outputs from each of the processes involved and provide a mechanism for analysing system costs.

Setting up the framework.

The viability of processing water hyacinth into energy and other outputs will depend on the values of the outputs and the costs of the inputs (primarily capital and labour). These quantities will vary with locality and scale of operation. To model their effect on profitability it is necessary to break down the whole process into a number of constituent stages (unit processes). Each stage can then be modelled in turn, and the overall costs and benefits of different configurations of the stages can be computed.

Table 4.23 identifies ten such stages, and for each lists, for a medium-scale plant, the probable relative size of its construction and operating costs. It also lists estimates of the effect on these costs of increasing the plant size. Costs that are shown as having a 'low' scale-up factor will be less significant in large plant than in small ones.

In Chapter 7 specific costs for two scenarios (Bangladesh 1988, Thailand 1992) are employed. In the current chapter the discussion will use unspecific costs. One of the shortcomings of many previous attempts at assessing commercial benefit has been the omission of certain key costs. It is, for example, often forgotten that water hyacinth requires to be harvested, yet the cost of harvesting is not insignificant. The relative costs presented in Table 4.23 provide an insight into the range of likely values that will need to be assigned to the individual stages. It is the relationship of these individual costs to the specific values that may be obtained from the selected outputs, in any one particular circumstance, that define the viability of the system.

It is necessary, therefore, to be able to estimate the relative capital cost of each of the stages. For example, the cost of the digester will in all probability dominate the capital cost of the whole system. It may be, however, that there is a point in which the cost of the digester and the cost of harvesting equipment will cross over in terms of significance. Set against the various costs and their relations will be the value of the products. In an idealised system, there will be a value assigned to gas, fertiliser and fibre. In reality, however, any one of these products may have zero value, whereas for example, the value of carbon dioxide may be the significant output. Once again it is necessary to arrive at algebraic relations for these various values in order that the relationship between cost and value may be modeled.

Growth

It is clear that as the throughput of the system is increased, the area of water required will similarly increase. This will be a linearly proportional relationship. The area of water required will involve a real or derived rental value. It may be that this figure will be insignificant in certain circumstances, but it should not be negated from the equation. Added to this may be the cost of nutrient input into the growth pond.

Where the water is part of a flowing system, nutrient requirements may be minimal. For example, the water hyacinth can be grown on the effluent from a sewage farm. In such a case, optimum benefit may be obtained both in terms of water hyacinth growth and water purification. There will remain, however, a manpower requirement, in terms of ensuring that growth is proceeding satisfactorily and that the system is being managed to optimise the output of the various products from the system.

As has been referred to earlier in the text, by managing such factors as plant density and nutrient composition, it is possible to vary the ratio of the leaf, root and stem. In a system where the fibre value is to be optimised at the expense of gas production, it would be advantageous to maximise the stem length. This may be achieved by maintaining high plant density. Set against this, however, will be the fact that as the plant density increases, the growth rate may reduce, and the overall production of organics will similarly reduce. Yet again, this reduction may be eliminated by increasing fertiliser and nutrient input to the growth pond. The fertiliser may be made up of the effluent from the anaerobic digester.

Table 4.23 Relative costs and scale-up factors for the various stages involved in utilising water hyacinth.

System stage (symbol for cost analysis)	Capital investment		Operation & maintenance	
	Relative costs	Scale-up factor [1]	Relative costs	Scale-up factor
Growth (G)	Low[2]	High	Low	Low
Harvesting (H)	Medium-high	Medium	High	Medium
Pre-processing (P)	Medium	Medium	High	Medium
Anaerobic digestion (D)	High	Medium	Medium	Medium
Storage of gas (Sg)	Medium-high	Medium	High	Medium
Fertiliser storage (Sn)	Medium	Low	Medium	Low
Fibre storage (Sf)	Low	Low	Low	Low
Gas distribution (Dg)	High	High	High	Low
Fertiliser distribution (Dn)	Medium	Low	Medium	Low
Fibre distribution (Df)	Low	Low	Low	Low

NOTES:

1. *Scale-up factors are based upon the ratio of cost to capacity. Where: cost = K x capacity$^{\alpha}$ where α is taken as 0.7 for a low increase in costs, 0.7 - 0.9 for a medium increase in costs and 0.9 - 1.0 for a high increase in costs.*

2. *Where it is necessary to cultivate the feedstock in special ponds rather than gather 'wild' water hyacinth, the costs will be high.*

Harvesting

The cost of harvesting water hyacinth is, similarly, linearly proportional to the size of the scheme, as far as any one method for any one scale is concerned. There is, however, the possibility of obtaining significant economies of scale by using more efficient methods of harvesting that require a larger initial capital cost. Where harvesting is mechanised, a growth area that keeps such equipment operational for twenty-four hours a day will maximise the benefits from mechanisation. In work carried out in the United States, (Wolverton, 1979), it was found that a roving mechanical harvester remained idle for the majority of the time. This occurred because it was able to harvest the daily requirement in a matter of hours. Obviously, such use of capital would not be satisfactory within a fully commercialised system.

It is unlikely that manual labour will be suitable for a scheme from which commercial benefit is to be obtained, except perhaps within the context of Bangladesh, where the cost of labour is very low compared to, for example, the cost of energy. This latter is driven by the international price of oil and bears no relation to the economy of Bangladesh. Manual harvesting has, however, been found to have limited scope. There is considerable evidence that the water hyacinth plant contains irritants to human skin and excessive handling of water hyacinth leads to significant skin irritation. For this reason, in Bangladesh, even moderate daily harvesting of water hyacinth commands a premium rate from unskilled labour. As with all costs, it will be necessary to ensure that the cost of harvesting is minimised. It is probable that the operational cost of this particular stage in the overall system will be of significance in relation to the operational cost of the other stages.

Pre-processing

The degree of pre-processing will determine the extent to which this step in the system affects the overall system economics. Experimental work, as discussed in the next chapter, indicates that the use of a slurrying and pressing procedure prior to anaerobic digestion will optimise the various outputs. This being the case, the energy requirement at this point in the system may be of significance. In practice it has been found that the energy for slurrying is approximately 150 kJ per kilogramme of juiced product. With a methane volume production of 280 litres per kilogramme, the energy required for juicing represents 15% on a thermal basis. Assuming electricity is produced with 30% efficiency the energy required for juicing will be 50% of that produced by 1 kilogramme dry weight of water hyacinth. This is assuming that 470 litres of biogas per kilogramme of water hyacinth with 60% by volume methane can be produced in a high-rate system. If the high-rate system significantly reduces the output of biogas per kilogramme this may have an effect upon the viability of the whole system, in purely energy terms. The system used in the current work will, therefore, require significant improvement prior to use in a full scale commercial system where energy in the form of methane is a major output.

Anaerobic digestion

It is this stage in the process that has been identified as likely to produce the most significant impact in terms of the overall economics. Subsequent economic arguments will confirm this assumption to be correct. The output of an anaerobic digester can be significantly varied by employing high-rate techniques. With a typical batch-digester operating on a thirty day retention time, reduction to a one day retention time will cause a dramatic reduction in the cost of the reactor. The scale-up costs will be similar for those of any such constructions but the starting point will be considerably reduced.

Storage

Gas storage of biogas will scale-up as for the storage of any gaseous product. There are many techniques available for reducing storage costs and making the product more suitable for use. The removal of carbon dioxide, for example, would reduce storage requirements by approximately half but would carry with it both an additional energy load and a significant capital cost. How these various costs will effect the overall economics will be the subject of localised market forces. It is probable that such techniques would not be viable unless the system were on a scale large enough to warrant their introduction.

Distribution

As with storage, distribution will be a function of the market size and demand. This will particularly affect gas and fertiliser. It is reasonable to assume that fibre will be distributed without difficulty. Gas distribution may be achieved by means of pipeline, compression cylinder or cryogenic liquid cylinder. On the other hand the whole question of storage and distribution may be obviated by using the gas to generate electricity. Electricity transmission is usually far more economically accomplished, given that the load requirement is adequate to allow the water hyacinth utilisation system to operate in a base-load condition.

Key system ratios

Given the extent of the variables that will be present in any one particular situation, it is a further requirement to arrive at key ratios by means of which the overall system benefit may be assessed. For example, it is possible to consider the energy yield per hectare as an indicative ratio, and, indeed, this is one that has been used often to justify the investigation of water hyacinth as an energy resource. However, the ratio of energy yield per unit of capital employed, is one that has, likewise, caused initial enthusiasm to wane. This second ratio is less readily assessed and yet its role in a viable commercial scheme may be dominant. Yet another ratio that must be studied is that of gas output per unit of capital employed in the anaerobic digester. This may further be reduced to unit of gas output per unit volume of digester. This latter is one of the key variables that will be addressed in the experimental section of this thesis.

The cost per unit volume of the digester is another ratio that significantly dominates and obstructs the implementation of large scale utilisation projects. Lecuyer, in looking at large scale gas production in the United States, considered the use of a 22 million cubic metre anaerobic digester (Lecuyer, 1976). This is a significant construction requirement and would present severe problems to potential investors, with regard to risk and system viability. It is extremely unlikely that any one scheme will commence on such a large scale. Rather, the probability will be a more gradual increase in size as the problems of scale-up are encountered and overcome. There is no question that moving from a laboratory-scale reactor into a commercial-scale reactor involves tackling many problems which are not apparent within the small scale environment of a laboratory.

Table 4.24 presents the key ratios within each stage of the system. Optimising each of these ratios will be primarily a matter of engineering design. In the case of gas production per unit of digester volume, the requirement is greater than simply design optimisation. Work to date has suggested that the possibility of high-rate anaerobic digestion is one that is real. Laboratory experiments have demonstrated the potential. In chapter three of this thesis various options for high-rate anaerobic digestion were considered. In the light of the dominant position of this key ratio within the structure of the overall system, it was proposed that preliminary experimentation should be directed towards assessing the viability of the multi-stage upflow anaerobic digester with water hyacinth juice as a feedstock.

For such work to be meaningful it must pay attention to the qualitative, as much as the quantitative, aspects of the process operation, addressing the question of operational viability as well as the more theoretical aspects of idealised system output. The problems of scale-up will be significant. There are several primary questions with regard to water hyacinth in high-rate digesters that can be assessed by means of laboratory and pilot-scale reactors.

Table 4.24 *A summary of the key ratios employed in evaluating a multi-output utilisation scheme based upon freshly harvested water hyacinth.*

Unit process	Ratio type	Key ratios	Name	Units
Growth	Economic	Product value [1] : unit-area cost [2]	G_e	£:£
	Technical	Useful biomass wt. : unit-area	G_t	kg:ha
	Linking	Useful biomass wt. : unit-area cost	G_l	kg:£
Harvesting	Economic	Product value : plant cost	H_e	£:£
	Technical	Useful biomass wt. : energy employed	H_t	kg:kJ
	Linking	Useful biomass wt. : plant cost	H_l	kg:£
Pre-processing	Economic	Product value : plant cost	P_e	£:£
	Technical	Useful biomass wt.: energy req'd	P_t	kg:kJ
	Linking	Useful biomass wt. : plant cost	P_l	kg:£
Anaerobic digestion	Economic	Product value : plant cost	AD_e	£:£
	Technical	Product output [3] : digester vol.	AD_t	kg:m^3
	Linking	Product output : plant cost	AD_l	kg:£
Gas storage	Economic	Added value : plant cost	GS_e	£:£
	Technical	Useful gas stored : storage vol.	GS_t	kg:m^3
	Linking	Useful gas stored : plant cost	GS_l	kg:£
Fertiliser storage	Economic	Added value : plant cost	FS_e	£:£
	Technical	Nutrient value : storage vol.	FS_t	N:m^3
	Linking	Nutrient value. : plant cost	FS_l	N:£
Gas distribution	Economic	Product value : plant cost	GD_e	£:£
	Technical	Useful gas distributed : energy req'd	GD_t	kg:kJ
	Linking	Useful gas distributed : plant cost	GD_l	kg:kJ

NOTES:
1. *All rate components, where applicable, are taken as being on a per diem basis.*
2. *Costs are taken as being operational costs plus capital costs converted to lease-costs.*
3. *Product output in this case is gas plus fertiliser.*

The number of key ratios is large. Each one, in its specific part of the system will have significance, whereas, within the system as a whole the impact will vary. Table 4.24 omits, for example, the relations affecting fibre storage and fibre distribution. These will have minimal impact on the overall system viability. In order to evaluate the relations between the ratios a "standard" scenario will be established in Chapter 7. This will be used to measure the relative importance of key ratios and also to assess the impact of varying input and output values.

A further method of analysing the economics of the system under review is to develop an economic model which can accept the various figures for input and output and arrive at an overall statement of the system viability. Figure 4.2 is a representation of a unit process within the overall system. There are effectively two inputs to each unit. The first is the feedstock to the unit, carried forward from the previous unit, and the second is the inputs required to make the unit function.

The processing of the feedstock to an output, or feedstock to the next unit, is a function of the feedstock productivity for unit "n" (FPn). The added costs incurred as a result of the unit process itself may be represented by process productivity (PPn). In the case of water hyacinth growth, for example, the feedstock productivity (FP1) will be the growth rate.

The process productivity (PP1) will be the effective rental value of the water area. The process productivity can be based upon several differing functions. For example, it may be measured as a product per kilogramme relationship or upon a product per unit of energy consumed. The feedstock productivity will be a rate function and, in view of the key importance of finance, it will be logical to arrive at a unit of cost per period of time, in this case days. This is capital productivity. Linking the capital productivity to the process productivity can be managed by means of an efficiency relation which converts process productivity into a rate relationship. By this means it is possible to combine the two productivities into one relationship per stage. The full system can then be effectively built up into a form for use in an economic assessment.(Figure 4.3) This will be the basis for the spreadsheet developed and discussed in Chapter 7.

4.6 THE CASE FOR JUICING

Separates fibre

Fibre has been proven to have a separate economic value by several researchers. Removing fibre from residual organics is a unit process that will allow for increased benefit to be obtained from water hyacinth. In order to remove the fibre, it is necessary to break down the structure of the plant. Once the structure of the plant has been thus reduced, it becomes a more readily achievable objective to remove the soluble component of the plant containing the organics for use in an anaerobic digester. This being the case the use of slurrying and pressing, described here as the juicing process, is one which would appear to have value in enhancing the overall system performance. The efficiency of these two processes is not the subject of the current study, other than to note that work in this area will be required.

Figure 4.2 Standard unit process

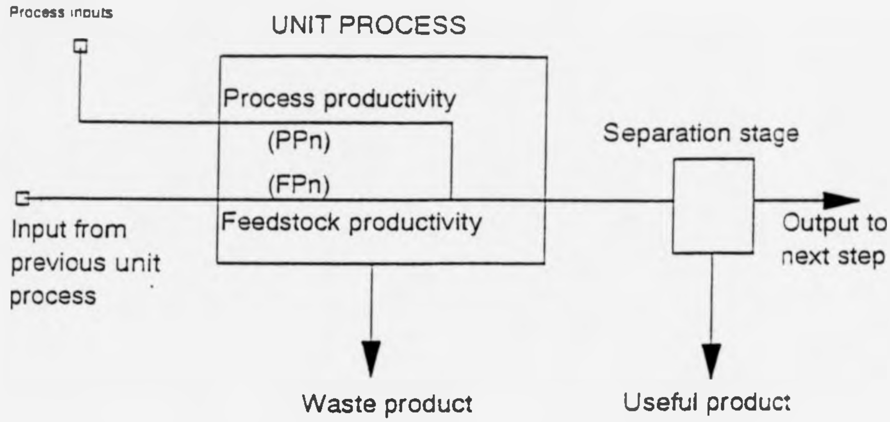
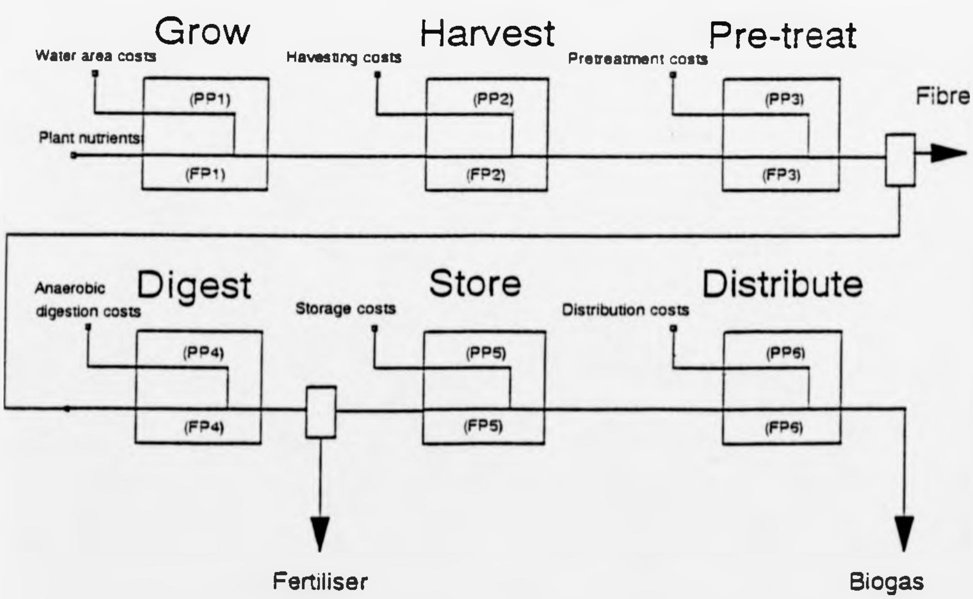


Figure 4.3 Generalised system presentation with biogas as the principal output



High rate digestion

As has been described earlier, in order to achieve high rate digestion it is necessary to have a soluble organic feedstock. Juiced water hyacinth is possibly a suitable feedstock for such systems. The insoluble solids content must be such that blocking does not occur on any significant scale. Where slurried water hyacinth is introduced into a multi-stage upflow anaerobic digester blocking will become a significant obstacle to its satisfactory operation, if it can operate at all. Juicing, or some similar system of concentrating the soluble organics, is, therefore, an essential prerequisite for the use of the system selected. Without juicing it is necessary to either find an alternative high-rate process or to reconsider the whole question of high-rate anaerobic digestion.

Hydrolysis

In order to accelerate the process of anaerobic digestion, it is necessary to maximise contact between bacteria and organic matter. Where the organic matter is contained in solution, the surface area will thus be maximised. Within the digester there are a number of critical path transformations which determine the rate at which the overall process occurs. One of these is hydrogenation, by means of which the organics are entered into solution. By partly carrying out this process mechanically outside of the digester it is reasonable to expect that the overall efficiency of anaerobic digestion will be increased. By using the portion of the plant that is already in liquid form we will greatly accelerate the overall process dynamics.

4.7 ISSUES FOR DETAILED EXPERIMENTATION

The analysis and deduction contained in the preceding chapters of this thesis have resulted in the selection of several key components within an optimised system for utilising water hyacinth. In order to increase the net benefit and make a biogas system commercially viable it will be necessary to employ high-rate digestion. From the various options available within this definition, the use of upflow digestion has been chosen as best suiting the substrate potential. From this position, the use of multi-stage upflow digestion would appear to hold potential for optimising the output of gas. In order that such a high-rate digestion unit should operate it will be necessary to solubilise the substrate prior to its addition to the digester. It has been decided that this can most readily be achieved by mechanical juicing. The remainder of this thesis is an examination of the workability of such a system.

Gas productivity from juice

One of the key factors to be clarified, with regard to substrate juicing as a method for increasing the overall system performance, is the ratio of available gas production, from a unit of harvested plant, with and without juicing. The key question is to assess the loss in gas production, if any, that results from the use of the juicing process. The concentration of soluble components in the juice will provide for a more rapid mass transfer from the organics that are soluble. It is inevitable, however, that the COD and VS concentrations of the slurry and the juice will be significantly different, these two measures including, as they do, organic components that would not be amenable to reduction by anaerobic digestion. Lignin, cellulose and hemi-cellulose will all contribute to the COD and VS figures but may not be available for gas production within a realistic time frame.

Desirability of separating the plant prior to digestion.

In prior experimental work it has often been the case that researchers have removed the root from the plant prior to digestion. In Bangladesh, as part of work carried out by the Housing and Building Research Establishment, the root and the leaves were removed prior to chopping the stem and feeding this into various types of anaerobic digester. It is, therefore, important to assess the need for separating the plant into its various components parts prior to digestion. This will also be of relevance with regard to the use of a multi-stage, upflow anaerobic digester.

Associated with this question of suitability of the feedstock to the process selected, is the question of determining the cost of preparing the feedstock for the process route in mind. At an extreme, it may be that the cost of feedstock preparation, in terms of energy input, will be greater than the energy produced. Determining this ratio of energy required per unit of energy produced is one that must be addressed, albeit at a broad level for the purposes of this work.

Workability of a multi-stage upflow anaerobic digester with juice.

Throughout the reasoning leading to the proposition that juicing is an essential requirement for high rate anaerobic digestion, it has been assumed that the use of juiced water hyacinth will not cause significant problems in a high-rate digester. This assumption is one which has followed on from a previous assumption that proved to have been erroneously made. Work carried out in Bangladesh in the course of this study was based upon the premise that because water hyacinth in its natural state has a low solids content it will operate effectively in a multi-stage upflow digester. The construction of such a unit in Bangladesh, and its initial loading with chopped water hyacinth stem, rapidly demonstrated that this would not be the case. A key question is to determine whether or not blockages of the selected process will occur with water hyacinth juice.

Digester optimisation.

A further area of interest will be to assess the digester design and to determine whether or not any modifications may be introduced to suit the condition of the feedstock. The unit under initial consideration has been tried and tested on fully soluble organic feeds. It is ideally employed with this kind of substrate. In the case of juiced water hyacinth, it is unlikely that the juice will contain only soluble organics. It may be that adaptation of the classic design should be considered to take this factor into account. Within the compass of the digester design, it would also be desirable to determine the optimum flow rate and the relationship between flow rate and biogas production/ COD removal. Optimisation will, therefore, involve partly geometric design and partly operational considerations. How important, for example, is temperature and what is the minimum residence time. How many stages should be employed in a multi-stage unit and what will be the overall effect be upon capital productivity.

Considerable data exists on the effect of selected and controlled temperature ranges on the performance of anaerobic digesters within a laboratory environment. This variable has not been selected for further evaluation. On the contrary, the effect of ambient temperature on the overall system performance would be one of interest. For this reason the digesters within the current round of experimentation were allowed to vary in temperature according to the ambient.

Efficient pre-digester separation (juicing).

In order to maximise the transfer of organics into juice by means of mechanical separation it will be necessary to view the options available. With regard to this specific point, it is not an objective in the current work to develop an improved juicer. Efforts have been contained in this area to selecting the optimum method of achieving the objectives with existing technology. This principle was expanded to encompass selecting suitable existing technology from indigenous sources. Development of improved juicers will the subject of a separate research exercise.

Plate No.1 *Water hyacinth pond, from where feedstock was collected, within the grounds of the Housing and Building Research Institute (HBRI), Dhaka.*

Plate No.2 *Loading pre-treated water hyacinth into the anaerobic reactor built with the grounds of HBRI, August 1987.*

Plate No.3 *Fibre removed by hand from the water hyacinth juice feedstock. HBRI, Dhaka, August, 1987.*

Plate No.4 *A flooded garage with water hyacinth. Dhaka, September 1987.*

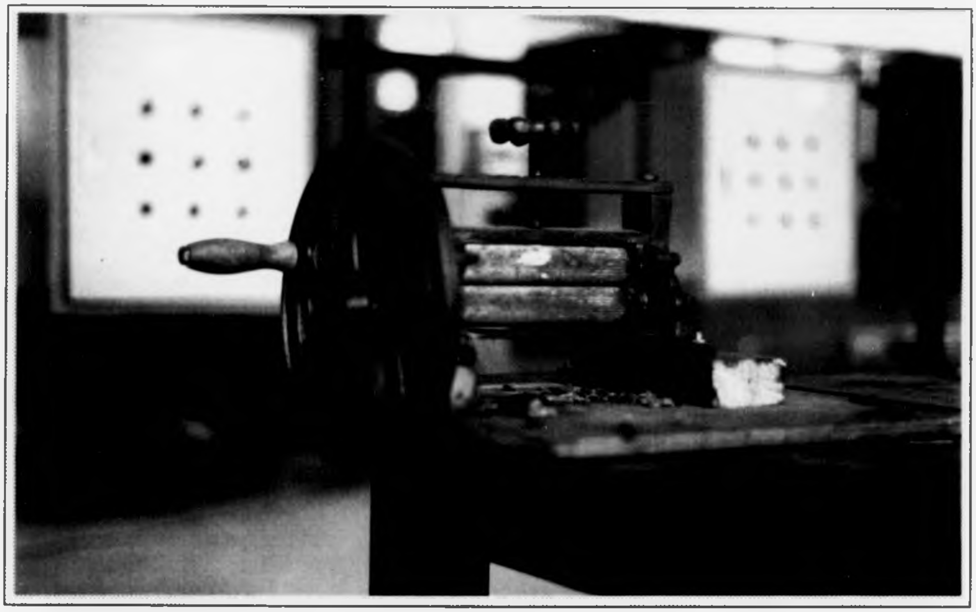


Plate No.5 *Squid roller, initially used for crushing water hyacinth and subsequently replaced by a mincer. Mahidol University, September, 1992.*

Plate No.6
Technical assistant passing water hyacinth leaves through the mincer with a manual press in the foreground, Dept of Environmental Sciences, Mahidol University, December, 1992.

Plate No.7 *Slurried water hyacinth leaf, after having been passed through the mincer.*

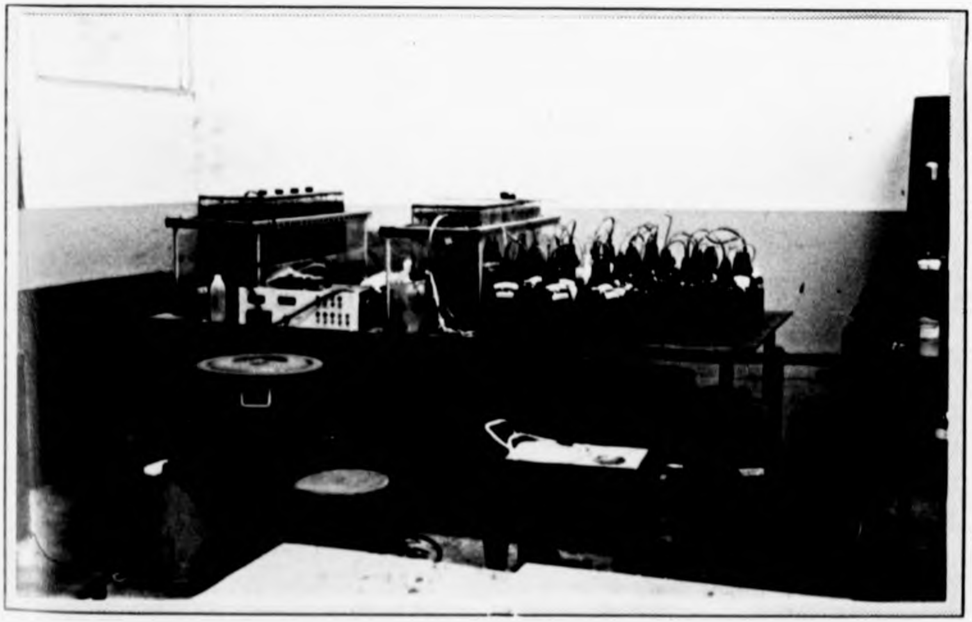


Plate No.8 *Experimental set up at Mahidol University, showing the batch reactors, the experimental multi-stage upflow reactors and the seed reactor on the floor to the right of the bench.*

Chapter 5

SELECTION OF PROCESS OPERATING PARAMETERS AND INITIAL EXPERIMENTATION

This chapter covers the construction and operation of a pilot anaerobic digester designed to operate on water hyacinth juice in Bangladesh and the operation of laboratory batch reactors in Thailand. From these initial investigations key parameters are selected for further experimentation.

5.1 INTRODUCTION

Researching water hyacinth from England, where the plant will not easily grow, has lead to numerous visits overseas. The history of the process of obtaining results is covered below.

England

As has been noted previously, water hyacinth does not grow in ambient temperatures of less than 20°C. A further requirement is that there is adequate insolation. Below approximately 1,400 lux the water hyacinth plant will be found to be dead or dying (Penfound, 1948). These two prerequisites have meant that growing water hyacinth in the quantities required for experimentation, and outside of the warmest summer months in the UK, is extremely difficult. The efforts to locate adequate water hyacinth with which to carry out the experimentation associated with this research work has been a saga in itself. The experimental programme was moved from Coventry to Dhaka, back to Coventry and finally to Bangkok.

Water hyacinth can be purchased in the UK in aquatic garden centres. The plant is grown in greenhouses in Europe and shipped to the UK for the commencement of the spring season. During the summer, a water hyacinth plant will generally survive on ponds in gardens in the UK. Its growth, however, is stunted as temperatures rarely remain at a level where luxuriant growth will occur.(See Figure 1.3) Should any cold spells develop, the plant will rapidly die off. Early attempts at growing water hyacinth in useful quantities in the UK, as part of this research effort, were unsuccessful.

Bangladesh

Links were consequently established with water hyacinth researchers in

India and Bangladesh. The Commonwealth Science Council had recently published the results of a UNEP sponsored research effort into water hyacinth and several teams were established in both of these countries. Following correspondence with Dr J N Baruah contacts were made with Professor Haider of Dhaka University, Bangladesh. Professor Haider had been the regional coordinator for Bangladesh and had played an important role in carrying the Commonwealth Science Council project forward. In 1986, a visit was made to Bangladesh to discuss the possibilities of collaborative research. Professor Haider, as Head of the Department of Chemistry, was able to draw in expertise from other departments as well as from Governmental institutions. Most of the work on water hyacinth utilisation had been carried out at the Housing and Building Research Institute (HBRI), located close to the university, and it was proposed that the new research should be similarly carried out at HBRI. The environment looked promising; in every direction water hyacinth was growing abundantly. Within the grounds of HBRI there was a large pond covered with water hyacinth. (See Plate 1) HBRI had been investigating the use of water hyacinth as a feed to a paper and board making process and had invested in a 50kg per day pulping plant. It was agreed that a trial multi-stage upflow reactor would be built and that experimental work would be carried out with the assistance of technicians from the Institute. There had, in fact, already been some experimentation with anaerobic digestion of water hyacinth, but this had proved unsuccessful. Using the Indian design of anaerobic digester, with a floating gas holder on top of the digester, water hyacinth had been introduced in various forms. The problem of floating and subsequent sinking had been encountered and initial attempts had been made to prevent this from occurring by using nets within the digester. The idea of using juiced water hyacinth within a multi-stage upflow reactor was, therefore, met with interest and, perhaps, a little scepticism.

During the course of the next eighteen months, a six cubic metre anaerobic digester was built. The first unit was made with a ferro-cement lid.(See Plate 2) This proved to be unsuitable, as the ferro-cement tended to crack allowing gas to escape. It was also extremely heavy to lift. Two new lids were made out of sheet steel. These did not leak and they could be lifted easily by two people. The problem with steel lids, and the reason that they were not initially selected, is that they tend to corrode around the immersed edges. It was recognised that steel would be an expedient to progress the current work and not a useful material for long term operation. In the summer of 1987, together with Dr Ania Grobicki from Imperial College, a visit was made to Bangladesh to commence operation of the multi-stage upflow reactor and to begin the associated laboratory work. This trip marked the unfortunate ending of the Bangladeshi period of this research effort. Considerable problems were encountered from the very beginning. A new Director had been appointed to HBRI and, despite the fact that the multi-stage upflow reactor was extant in his grounds, he required additional convincing that his institute should be involved in such work. He quite reasonably pointed out that the Housing and Building Research Institute was not perhaps the most logical place in which to experiment with anaerobic digesters. After assuring him that no funds were required from HBRI and that, on the contrary, funds were being made available to HBRI employees to subsidise their salaries, we were able to pass over this hurdle. The next problem encountered was that of the laboratory experimental work. It was discovered to be extremely difficult to procure even the most basic of chemicals for carrying out laboratory analysis. For example, it was necessary to find a bottle of sulphuric acid for COD tests. After two or three days searching through the market of Dhaka a bottle of 1N sulphuric acid, suitably marked "Made in Germany", was obtained. It was rapidly discovered, however, that the "Made in Germany" label had probably been made in Bangladesh and that the sulphuric acid had been heavily diluted prior to sealing, and was, therefore, not suitable. It was decided at this point that COD testing would be abandoned for the present and continued when suitable chemicals could be procured, perhaps from the United Kingdom.

The final blow to the Bangladeshi period was yet to come. The weather during the last visit to Bangladesh had been very pleasant. There had been no sign of rain and the temperatures were not excessive. However, flooding was occurring in the north of the country, resulting from heavy rainfall in the Himalayas. Deforestation in the foothills of the Himalayas was believed to be allowing exceptional run off during rains in that part of India. Gradually the flooding moved south towards Dhaka and, as luck would have it, on the very day when the multi-stage upflow reactor was due to be started, after a period of inoculation and acclimatization of the anaerobic bacteria to the water hyacinth substrate, the grounds of HBRI were flooded. The journey to HBRI from the university residence was usually accomplished by a local taxi in twenty minutes. On this particular day it was necessary to take three boats and four short walks to complete the same route. After investigation, it was clear that no further work could be carried out with this multi-stage upflow reactor until the flood receded. There was also the possibility that it would not be possible to leave the country until the flooding abated as the rising water level was beginning to cover the airport runway. Upon receipt of this news there followed an undignified dash to the university residence to collect all belongings and depart for the airport. En route it was apparent that water levels were rising dramatically in all quarters, the population had moved from their dwellings onto raised highway embankments and these were now lined with cattle, families and make-shift huts. The rising water surfaces were covered with hugh mats of luxuriant water hyacinth reaching in all directions. As soon as flood waters entered new premises they were very rapidly followed by water hyacinth hungry for fresh space. (See Plate 4)

Following on from this experience, some attempts were made to restart the multi-stage upflow reactor in the grounds of HBRI, but the feeling was, despite the expertise and enthusiasm of very senior staff, that the problems associated with attempting to carry out such research work in Bangladesh were too great to be accomplished at a distance, on a limited budget. It was, therefore, decided to look elsewhere for water hyacinth feedstock for the experimentation.

England re-visited

Shortly after the following New Year, it came to the notice of the author that a water hyacinth propagator was in the possession of the technical director of a company called Farm Gas Limited. He had been growing water hyacinth in his garden, in the Welsh mountains, in an attempt to investigate the purification of waste water, from the anaerobic digestion of farm manure, by means of heated water hyacinth ponds. His work, now completed, meant that the water hyacinth propagator was available to an interested party, free of charge. This propagator was duly collected and installed on the roof of the Engineering Department at Warwick University. It was placed in this location for a number of reasons, primary amongst which was the level of insolation that it would receive from its south facing aspect. There was also power at this location to operate the plant heater and ready access was available from the Engineering Department itself. It was in fact the ideal situation, as long as the plant could be encouraged to grow at an adequate rate for the experimentation.

Shortly before water hyacinth was introduced into the digester, and while it was temporarily emptied and unanchored to permit roof repair, a hurricane struck the United Kingdom, resulting in extensive damage. A local result of this wind was that the propagator was lifted from the roof of the Engineering Department and deposited in the street, four floors below. The destruction of the propagator, being manufactured from fibre glass, was near complete. It was fortunate that no injuries resulted. Whilst it was acknowledged that this was an exceptional storm, and unlikely to occur again, it was felt that it would be better to place the propagator at ground level.

The propagator was moved to a garden in Kenilworth and connected into a domestic electricity supply. It was recognised at the start of this period that the electricity bill would be high. In comparison to the cost of working overseas it was decided that this would probably be acceptable. The propagator was duly repaired and re-erected and connected to the electricity supply. Initial results were promising. Water hyacinth obtained from the local aquatic garden centre, in the late summer of 1988, grew encouragingly and it appeared that the problem of feedstock availability had finally been resolved.

However, as the ambient temperature fell with the approach of winter, the electricity bill began to soar, perhaps more than was anticipated from the initial calculations performed with regard to heat loss and power requirement. A further factor, outwith the control of the researchers, was that the level of insolation was dropping dramatically. It was necessary to cover the water surface with a twin-wall polycarbonate sheet in order to retain heat, but this material also cut back already low light levels and caused the plant growth to drop off significantly. From an initial period of rapid growth the water hyacinth moved into a static condition and growth ceased during the winter months. It became a very expensive activity simply keeping the plant alive. During the commencement of the New Year, it was decided that the propagator should be switched off and the plant allowed to die. The accumulating electricity bill was growing to a level where work overseas appeared, once again, to be a more economic and attractive option.

Thailand

As good fortune would have it, contacts with the newly formed Department of Chemical Engineering at Mahidol University in Bangkok, Thailand, developed at around this time. After initial discussions, it was agreed that the experimental work could proceed within the limited laboratory space of the new department. Prior to commencement of work at Mahidol University, it was necessary to set up the administrative framework in which the experimental work could occur. Following visits of the Head of the Department of Chemical Engineering and the Dean of the Faculty of Engineering to England, an official link was signed between the two departments enabling research work to occur within a broader framework of understanding and cooperation between the two universities. Construction of new experimental apparatus finally began within one of the outbuildings of Department of Environmental Sciences during the winter of 1991 to 1992.

As with the situation in Bangladesh, there was an abundance of water hyacinth close to the experimental work station. In the case of Thailand the water hyacinth was growing wild within ponds in the university grounds. It was a matter of a two minute walk to obtain as much water hyacinth as would ever be necessary. A laboratory technician was also available from the Department of Chemical Engineering. The department was still in the initial stages of formation and the technician had very little work to do. Thailand offers a much improved opportunity, over that in Bangladesh, for successfully carrying out research work. The general infrastructure of the country is by and large operational and effective. It is possible to procure all the ingredients that might be required at any particular moment without difficulty. Experimental work commenced with the construction of three multi-stage upflow reactors, each with a capacity of 50 litres. In the summer of 1992 it was possible to obtain seed material with which to commence the anaerobic digestion process, and during the winter of 1992-3 the bulk of the experimental work was completed.

5.2 INITIAL EXPERIMENTS (BATCH DIGESTERS)

From a position of theoretical understanding of the problems and potential for use of water hyacinth it was necessary to establish basic aspects of the plant's utility in the processes of interest. Initial experimentation was directed towards characterising the plant.

5.2.1 Objectives

Determine feedstock preparation method and assess its impact on the overall process

A primary objective of the research was to establish high-rate anaerobic digestion techniques. The high-rate digester chosen was a multi-stage upflow reactor. Experimental work was directed at evaluating methods of feedstock preparation and determining the workability of the multi-stage upflow reactor with water hyacinth. This included assessing the gas production rate, determining whether operational problems would develop and evaluating the realistic possibility for application. The initial experimentation was carried out in Bangladesh. At the commencement of this work it was intended that a multi-stage upflow reactor should be built within a local village community. In the event the obstacles to progress were of such a magnitude that this final step was not possible. Prior to the washout of the experimental multi-stage upflow reactor within the grounds of HBRI it was, however, possible to carry out preliminary evaluation of both feedstock preparation and of the workability of the multi-stage upflow reactor with the feedstock so prepared.

This initial work was built upon, whilst in Thailand, by evaluating other forms of feedstock preparation and carrying out a comparison with the information obtained from Bangladesh. One key constraint upon the attempt to optimise feedstock preparation was the need to use locally available machines. In the case of Bangladesh, the machinery for this stage in the process was already available within HBRI. The personnel working at the institute had been preparing water hyacinth for the paper and board making process for a number of years and, by a minor degree of adaptation, it was possible to use the installed equipment to prepare the feed for an anaerobic digester.

Demonstrate multi-stage upflow reactor workability with suitably prepared feed stock.

Within the framework of assessing the principle bottlenecks within the overall system it is necessary to determine whether or not technology that is available for resolving such bottlenecks will, in fact, be workable. As mentioned previously, the anaerobic digestion stage of this system, and indeed any system which seeks to extract energy from biomass via methane, is one which runs a severe risk of causing a primary imbalance in terms of capital expenditure, operational costs and revenue. The multi-stage upflow reactor, having been selected by means of analysis and deduction, required to be investigated in a practical and meaningful manner. It was, therefore, desirable to build a multi-stage upflow reactor, in a situation similar to that in which it may be employed, on a reasonably representative scale, and to observe any difficulties that might result from the use of this technology. The multi-stage upflow reactor has been amply demonstrated in the laboratory and it is clear that the strategic scientific technology involved in its operation is likely to be of benefit. However its performance, with regard specifically to water hyacinth as a feed stock, remained in doubt.

Observe levels of gas production and any operational problems that might occur.

At the same time as investigating the various operational factors that may inhibit the performance of the multi-stage upflow reactor with water hyacinth as a feedstock, it was also a requirement to determine whether or not the high-rate anaerobic digestion was proceeding as expected. Considerable experimental data exists in the literature regarding output from laboratory anaerobic digesters. Similarly, considerable work has been carried out developing kinetic models for the estimation of gas production rates in relation to organic loading and other factors. (McCarty,1964 & 1972; Chen,1978 & 1980; Ghosh,1985). It was, therefore, determined that, against the background of this existing wealth of information, it was important to arrive at an estimate of the practical and realistically attainable output from a multi-stage anaerobic reactor operating with water hyacinth as a feed. Coupled with this requirement was a secondary requirement to determine whether the process of juicing would result in an overall improvement in the system as a whole. On one hand, the juicing process will concentrate the soluble organics and prepare the feed stock in such a way that it will be more amenable to use in an multi-stage upflow anaerobic digester but, on the other hand, there was concern that the process of separation itself might be the source of the loss of a significant percentage of the potentially anaerobically digestible organic content. With a readily available feedstock this would, though, not necessarily be an overriding consideration.

Assess indigenous community acceptance

Following discussions with various learned bodies in Bangladesh, it was emphasised that one of the principle, non-technical barriers to the implementation of viable systems, particularly in the Bangladeshi rural community, was the level of community acceptance. This was a barrier that would be difficult to investigate on a purely anthropological basis and it was set as an associated objective to assess the types of social reaction that may be encountered to the use of anaerobic digestion of water hyacinth on a community scale.

It should be mentioned here that the primary scope of the current work is technical in nature and it was, therefore, only as a matter of interest that this last objective was set. In practice, however, it proved not to be feasible to operate an anaerobic digester in Bangladesh, let alone in a Bangladeshi village, and for this reason the socio-economic aspect was taken no further than discussions and preliminary assessments. The results of this initial work will be discussed in the sections covering the possibility of implementation in Bangladesh. (See Chapter 7)

5.2.2 Experimental apparatus

Bangladesh

With regard to many aspects of the research, Bangladesh is an ideal location for carrying out pilot plant studies on anaerobic digestion, especially of water hyacinth. Discussions with the Housings and Building Research Institute (HBRI), as well as the Institute of Fuel Science (IFS) indicated that both HBRI and IFS were interested in the possibility of constructing an experimental reactor within their grounds. Both institutions had a number of existing reactors with varying designs and capacities ranging typically from 2 to 5 cubic meters. After evaluation of both sites, as well as the technologies and resources available, it was decided that HBRI would be a better location. The prime reason for this choice was that within the grounds of HBRI was a substantial body of water populated with water hyacinth. HBRI is the home of a paper-making plant, using the stem of water hyacinth, funded by the Commonwealth Science Council. The institute was equipped to facilitate daily harvesting of the plant and the necessary pre-treatment. HBRI was already operating a method of chopping and beating water hyacinth stems in preparation for the pressure-cooking process required for making paper and board pulp. There was also a reasonably equipped laboratory with technical assistance available to carry out tests such as COD and suspended solids.

Both the chopper and the beater used for feed preparation were capable of processing 10 kg/hr dry weight of water hyacinth. The power input was 1 kW to the chopper and 30 kW to the beater. The beater consisted of a paddle arrangement above a circular channel through which chopped water hyacinth stems were fed. Upon the completion of adequate beating the fibres were separated out by hand from the resultant slurry. (See Plate 3) It was not energy-efficient to run this process for the preparation of juice. The two machines together consumed 470 % of the maximum possible energy output of the anaerobic reactor on a daily basis. Alternative pre-treatment methods had to be considered to increase energy efficiency.

A six cubic meter reactor was designed for construction within the grounds of HBRI. HBRI, at the time, was also developing a technique for building with ferro-cement. At first it was considered that ferro-cement would be a suitable medium for building the digester walls and lids. After further consideration, however, it was decided that it would be better to place the container within the ground and build the walls with brick, lining them with a cement finish. The lids were, however, manufactured from ferro-cement. During the first trial runs of the plant, it was discovered that the ferro-cement was not, in fact, gas tight and, after several attempts at repairing the ferro-cement, it was necessary to replace these lids with sheet carbon steel lids. A further problem with the ferro-cement was that the lids were extremely heavy and it was necessary to have a minimum of 4 people to lift one lid.

Thailand

Following on from the work carried out in Bangladesh it was decided that it would be useful to produce smaller anaerobic digesters, thereby providing the possibility for testing independently several of various parameters involved in the process. Three reactors, each of fifty litres volume, were manufactured from perspex. The infra-structure in Thailand is considerably more advanced than that in Bangladesh. A greater scope was available for the selection of materials and methods. A further outcome from the preliminary work in Bangladesh was a recognition that the process of separation was one which would require greater emphasis. The selection of a process for juicing involved a detailed search amongst the various markets and bazaars of Bangkok for suitable equipment. Within the financial constraints of the research project, it would not have been possible to purchase equipment in the UK. The cost of fabrication for an idealised unit was also out of the question. It was felt that there would be considerable merit in using locally available technologies to achieve a realistic assessment of system viability with regard to this particular stage in the process. At an early point in the development of ideas within the research project it was decided that the efficiency of the juicing process was not one that should be addressed, in terms of building and testing equipment. Rather, the methods employed and the energy requirements should be studied so that an understanding of the principles involved could be developed.

It was for this reason that a classical food mixing juicer was the first item purchased for the juicing process. This provided a high-speed, and highly inefficient, opportunity for obtaining small suspended-solids particle size and good solubilisation. In reality, however, it was found that the juicer blocked very easily and was not strong enough to withstand the work required. The wet weight of water hyacinth harvested each day was significant. Within a comparatively short period of time the domestic juicer broke down.

The next piece of equipment investigated for juicing water hyacinth was a squid roller. (See Plate 5) A squid roller is very similar to a sugar cane crusher except much smaller and, thus, less expensive. In the market places and on the streets around both Bangladesh and Thailand it is possible to buy sugar cane juice. This is crushed from raw sugar cane sticks, whilst one waits, by means of a ribbed twin-roller. The ribs on the rollers are interlocking and provide a very effective crushing and juicing action. The squid roller was purchased to assess the effectiveness of this juicing action with water hyacinth. In practice it was found that the squid roller was not suitable for the duty. The reason for this is that the spacing on the roller is mechanically pre-set. Therefore, if the feed is of approximately the right thickness it will pass through the roller and provide suitable crushing. However, if the feed is too thin it will not be crushed adequately and if it is too thick it will not pass through the roller. The roller is a manual system and, combined with the problem of obtaining exactly the correct feed thickness, the throughput per day was very low.

The next locally available item selected for investigation was a mincing machine. This is a classic sausage feedstock processor and comes with either a manual drive or a motor drive. In view of the slow throughput experienced with the squid roller, a motorised-drive unit was purchased. The mincing action involves an auger-type of feed mechanism, pushing the chopped biomass towards the exit where a circular slicing action against a perforated exit-plate completes the crushing and chopping. The product from this particular system was found to be very suitable for the overall process. The feed was found to require a certain amount of pre-chopping in order that the mincing machine did not jam up, but the effluent was very effectively slurried.

In practice the first mincing machine purchased was found to be inadequate. It had a one-half horsepower motor and it was found that, with the stem in particular, the fibres caused the rotor to jam and eventually the half horsepower motor burnt out. An overload breaker for such a small single phase motor was impossible to find so it was necessary to manually switch the motor off whenever the mincer jammed. A one horsepower motor was subsequently obtained and this performed the duty without any difficulty. Jamming was no longer a significant problem. In practice the drive would keep turning but if excessive blockages occurred in the mincing machine the outlet would plug up and juice would fill up and overflow from the inlet side. At this stage it would be necessary to disassemble the unit and clear the blocks.

The slurried product from the mincing machine was subjected to a manual screw-press. This, again, was purchased in the food processing section of a Bangkok market. This item was a classical manual screw-press. (See Plate 6) The bulk of the experimentation with the multi-stage upflow reactors was carried out with feed prepared by the mincer and the screwpress.

In order to measure carbon dioxide and methane, two dual-beam infra-red gas analysers were brought over from the UK. A single-point thermocouple with a multi-point switch was used for measuring temperatures at various locations on the various reactors. In practice, however, it was found that the thermocouple temperature drifted severely, possibly due to a faulty transducer, and temperature levels were subsequently obtained with a mercury thermometer. Litmus paper was used to measure pH. An electronic pH meter was used initially but the accuracy of this item was suspect. It was decided that it would be better to stick with litmus paper for consistency. Measurements of COD, suspended solids and other such parameters were obtained with the assistance of the laboratory within the Department of Environmental Sciences. This laboratory was particularly well equipped and the technicians were able to provide a good service for the measurement of these parameters.

Seed material preparation

To commence the anaerobic digestion process without waiting an excessive amount of time for the generally ubiquitous anaerobic bacteria to develop, it is necessary to prepare a seed material. The seed would ideally be adapted to the substrate being utilised in the anaerobic digester. Anaerobic bacteria develop preferentially for different substrates at different temperatures. For the purposes of the current experiment, where time was at a premium, it was initially intended to use cow dung. Close to the university was a farm with cattle being reared for milk production. In practice, however, when the cow dung was mixed with water hyacinth, anaerobic digestion was not found to commence very rapidly.

An alternative source of initial seed was sought in a sewage works. A supposed tertiary treatment sludge was obtained for this purpose, although its poor performance possibly indicates that the problem of communicating technical terms may have intervened. It was found that this tertiary treatment sludge was not a significant improvement upon cow dung. One of the fifty litre multi-stage upflow anaerobic digesters was seeded with 30% tertiary treatment sludge, the remainder being slurried water hyacinth. The reactor was operated for a period of two and a half months but the results were so poor that they are not reproduced in this thesis.

The conclusion arrived at was that the adaptation of the anaerobic bacteria took most of this period and that the low levels of gas production and COD reduction were as a result of the lack of suitably conditioned bacteria. Similar results were obtained with water hyacinth seeded with cow dung. For the high-rate anaerobic digestion of water hyacinth it is essential to have a culture adapted to water hyacinth if satisfactory results are to be obtained. For this reason the start up period may be significantly longer than is suggested in the literature.

After the first two and a half month period suitable seed material was adapted to water hyacinth as a substrate. From the commencement of work in Thailand a separate seed vessel was maintained. (See Plate 8) This had a capacity of 40 litres. Seed was removed from the base of this reactor vessel and new substrate was placed in through the top. A paddle-mixer was operated through a gas seal in the lid. Occasional blockages were experienced within this vessel and for this reason it is suspected that the seed quality may have varied from sample to sample. When the seed was particularly watery the concentration of bacteria may have been less. On occasion, the seed material produced was thick with an apparently higher solids content. It was not possible to mix seed material effectively after it had been removed from the seed preparation vessel as this action may have killed the methanogenic bacteria.

The results of this lack of uniformity in seed bacterial concentration is manifest in the results from the batch trials. This effect was not so marked in the case of runs on the multi-stage reactors. It may have been that the poor seed was fairly rapidly discounted as the feed stock was in fact suited to the bacteria and the bacterial colonies grew comparatively quickly. It may simply have been a matter of fortune that the continuous reactors were seeded with good material.

Batch reactors

A series of batch reactors were set up to compare the static performance of various water hyacinth preparations. The vessels used were 3.3 litres in volume and made of brown glass. A single hole bung was used to plug the neck. From this hole gas was allowed to escape into another jar filled with water. This jar was plugged with a two hole bung, one to allow gas in and the other to allow displaced water to exit. The jar containing water was filled every day so that a more or less constant pressure was maintained. Gas analysis was carried out by drawing gas out with the analyser pump and drawing water back into the jar. During analysis, it was necessary to watch carefully because when the gas was fully evacuated from the glass jar, water could be drawn into the gas analyser. The batch reactor was inspected every day and turned upside down in order to provide some rudimentary mixing.

5.3 RESULTS FROM INITIAL EXPERIMENTATION

Preliminary experimentation took place in both Thailand and Bangladesh. Preliminary experiments were carried out with the objective of characterising the feedstock obtained from water hyacinth, prior to actually charging the experimental multi-stage upflow reactor. In Bangladesh much of the preliminary work was performed by the technicians at HBRI.

5.3.1 Results from work in Bangladesh

Total suspended matter and total dissolved matter in the water hyacinth feedstock.

The feedstock was prepared by (i) chopping the whole plant with a hand chopper and (ii) chopping the whole plant with a 2 hp electrically operated chopping machine. These chopped samples were macerated with water and placed in (a) aerobic conditions and (b) almost anaerobic conditions. At the start of the experiment and at intervals of 3, 7 and 10 days the fibrous materials in the samples were separated from the liquid portion by means of a 5 mm sieve. The liquid samples were filtered and the quantities of suspended matter and dissolved matter were determined as shown in Table 5.1. The machine chopping of samples resulted in higher levels of initial dissolved and suspended matter, both initially and with the passage of time. This results from the greater amount of breakdown of the plant structure achieved with mechanical action. It is interesting to note the fall off in levels towards the end of the experimental period. This is probably due to the commencement of digestion, both aerobic and anaerobic respectively.

Table 5.1 *Total suspended matter (TSM) and total dissolved matter (TDM) in the whole fresh plant (100 g) macerated with 900 ml water and allowed to stand.*

Process	TSM (ppm) Duration in Days				TDM (ppm) Duration in Days			
	0	3	7	10	0	3	7	10
Hand chopped (aerobic)	620	1210	1700	1932	594	1702	2298	1380
Hand chopped (anaerobic)	620	1154	1630	1336	594	1646	1492	1258
Machine chopped (aerobic)	1248	1716	2082	1894	982	2250	1638	1908
Machine chopped (anaerobic)	1248	1410	2190	1604	982	2440	1592	1574

Measurements with 2% cow dung mixed with water hyacinth extract.

The above series of experiments was repeated with 100 g of machine chopped plant, with an addition of 2% (dry weight) cow dung. The extracts with water were prepared as before and the quantities of total suspended matter and total dissolved matter were determined after 3, 7 and 10 days on separate samples. The results are shown Table 5.2.

The decrease in the total suspended matter, both in the aerobic and anaerobic conditions, will be as a result of digestion. The increase in total dissolved matter (TDM) after 10 days may be as a result of the release of more refractory organics in solution during the hydrolytic phase of digestion.

Aspirator bottle experiments for biogas production with pre-digested water hyacinth.

Water hyacinth biomass was pre-digested by holding it in both a polythene bag and an earthenware sealed container. The biomass so formed was tested for gas formation in an aspirator bottle of 3 litres capacity, mixed with water. Gas collection was facilitated by the downward displacement of water in a sealed measuring cylinder. The results of gas generation are shown in Table 5.3.

Table 5.2 *Total suspended and dissolved matters of machine chopped fresh water hyacinth (100 g) mixed with 2% cow dung in 900 ml water.*

Process	TSM (ppm) Duration in Days			TDM (ppm) Duration in Days		
	3	7	10	3	7	10
Machine macerated (aerobic)	-	29076	2094	5024	2308	6520
Machine macerated (anaerobic)	-	10620	1240	4698	2604	2920

The gas generation in both cases appears to show an increase in volume of production and confirms the previous observations that pre-digested water hyacinth biomass may be suitable for biogas generation. However, how this pre-digested water hyacinth will behave when charged in a multi-stage upflow reactor in bulk quantity is not difficult to imagine with the wisdom of hindsight. The fibres in the stems would block it completely. It is clear that where there are any appreciable suspended solids in the substrate, let alone long fibrous stems, such reactors will not function. The major production in biogas appeared after 14 days and this is still too long a period to meet the objectives of the current thesis.

Table 5.3 *Production of gas from pre-digested water hyacinth (1000 g) mixed with 2000 ml of water.*

Process	Gas generation in cm^3 per period Duration in days				
	7	14	28	50	60
Predigestion in polythene bag (28 days)	250	25,000	3,700	4,000	4,110
Predigestion in earthenware container (40 days)	315	29,000	3,950	4,230	4,030

Determination of weight loss of chopped water hyacinth in different aerobic and anaerobic environments.

These experiments were carried out to observe the natural degradation of chopped water hyacinth under different conditions with a view to ascertaining the normal degradation of biomass in nature. The loss of weight in air and in the absence of air give an indication as to the nature and rate of degradation. Water hyacinth proved to be such a robust plant that even in the chopped condition and in the absence of air there was not much loss of weight of the biomass, as indicated in Table 5.4. The weight loss recorded in aerobic conditions was due almost entirely to drying of the plant material.

It is quite evident that degradation does not easily commence chopped water hyacinth in ordinary conditions, even in an anaerobic atmosphere. The addition of cow dung and rumen in the feedstock of a multi-stage upflow reactor was considered necessary to accelerate the process of decay.

Table 5.4 *Weight loss of water hyacinth in different arrangements with time (days).*

Sample Preparation	*% Weight loss after:*	
	3 days	*7 days*
Hand chopped, anaerobic, plants arranged vertically	1	1
Hand chopped, aerobic, plants arranged vertically	33	92
Hand chopped, aerobic, plants arranged in a heap	28	66
Machine chopped, aerobic, plants arranged vertically	59	72
Machine chopped, aerobic, plants arranged in a heap	59	64
Machine chopped, anaerobic, plants arranged vertically	1	0
Machine chopped, anaerobic, plants arranged in a heap	2	2

A working model of a multi-stage upflow anaerobic digester was designed. The design and method of construction was agreed with the staff of HBRI. Much of the construction and research work involved n testing the unit was carried out by the scientists and engineers of HBRI from February 1988. The direction of study was mainly concerned with feedstock preparation. The solubilisation of water hyacinth biomass by various methods of pre-treatment such as pre-digestion, maceration, chopping, juicing and rumen-fluid treatment were evaluated in trials with the reactor. The intention was that the performance of the digester would be assessed operating with feedstock prepared by each of the different processes. In practice the trials resulted in a greater understanding of the problems associated with operating a multi-stage upflow reactor with suspended solids in the feedstock.

The proposed reactor, with a working capacity of 8.3 cubic metres, was constructed at the premises of HBRI. It was of interest to note the problems associated with construction of the reactor. A diagram of the installed multi-stage upflow reactor is presented in Figure 5.1. The following are some notes upon the construction of the multi-stage upflow reactor at HBRI:

1. The original design was revised by changing the construction material of the outer wall of the reactor from ferro-cement to ten inch brick-work. The inner volume remained unaltered at 8.3 m^3. After evaluation it was clear that ferro-cement would not be as strong and that a chamber built into the ground would also afford some degree of thermal buffering between day and night temperatures.

2. The construction work of the multi-stage upflow reactor took about one and a half months to complete. This seems an exceptionally long period but is more a reflection of the fact that a good deal of discussion and reappraisal occurred during its construction, rather than the complexity of the task itself.

3. It was initially estimated that the construction of the proposed model would cost about 20,000 Taka (Tk), but in practice, as a result of the change in construction materials and construction technique, plus alterations in the design, some additional expenditure was incurred, increasing the final cost to about Tk.25,000. (£1 $\simeq$ Tk.40)

On completion of the construction of the multi-stage upflow reactor, an attempt was made to load the digester with water hyacinth juice produced by the 20 hp beating machine. It was decided to use this beating machine as it was available, extant at HBRI from a previous

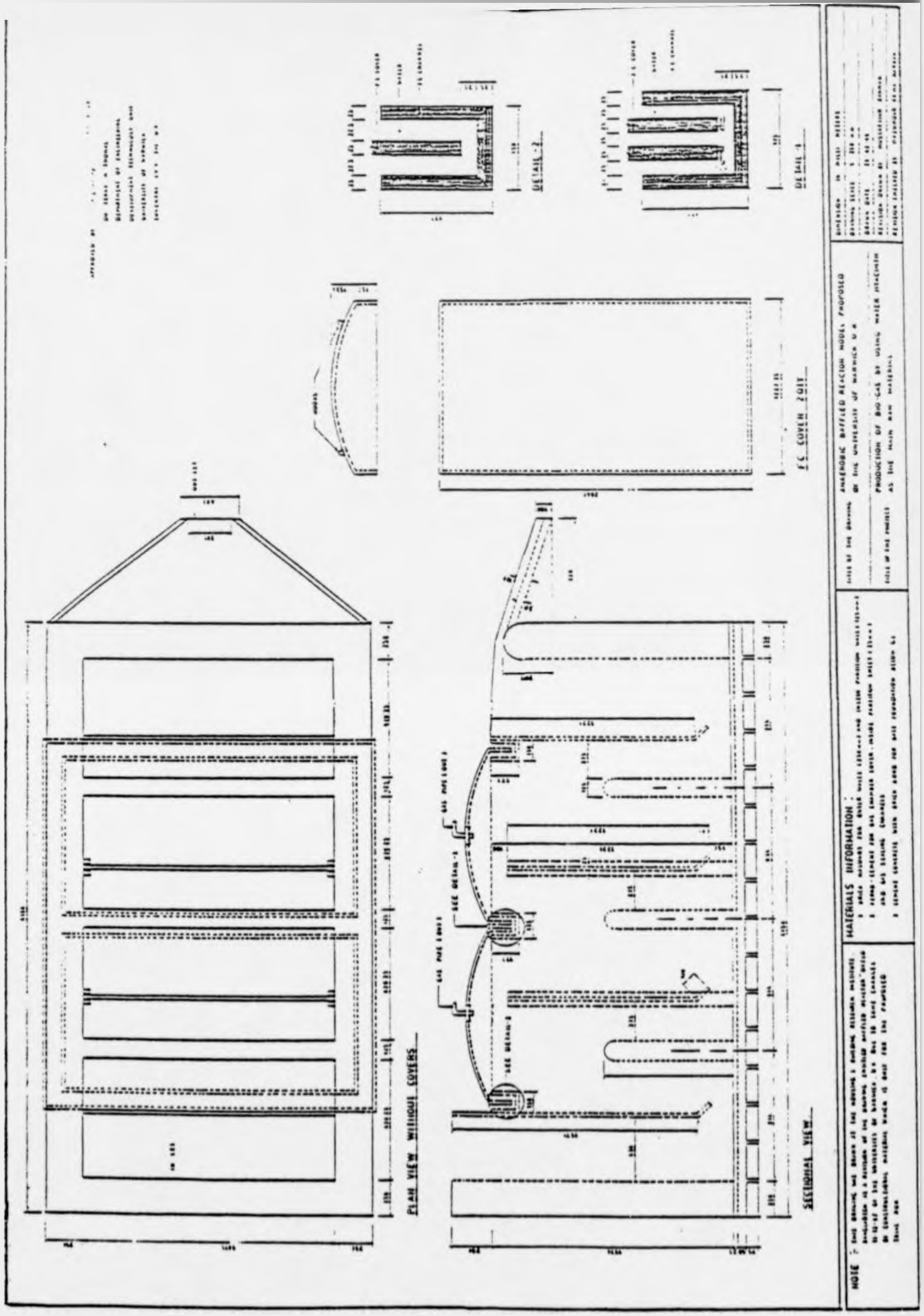


Figure 5.1 Multi-stage upflow reactor

Commonwealth Science Council project for paper and board production. The question of efficiency of juice production was a secondary consideration at this stage in the work.

As a result of heavy rainfall through to July 1988 all attempts at charging the reactor failed. The full internal volume of the reactor was flooded with rain water. In the month of August 1988 the first trial run was started with water hyacinth juice. The result was deemed unsatisfactory because of the small volume of gas produced. Flow was not achieved through the multi-stage unit as a result of outlet design difficulties.

The internal wetted volume of the reactor was subsequently reduced to 5 m^3 by cutting the outlet wall with a 50 cm slot. This facilitated charging the reactor with less juice and the storage of a larger volume of generated gas within the reactor itself. In order to accelerate the fermentation process, rumen fluid from a cow's stomach, collected from the local market early in the morning by Dr.Grobicki, was added to the reactor contents. Fresh slurry from a running biogas plant, operating on cow-dung, was also added into the water hyacinth juice. This material was added to all the compartments of the reactor. The staff at HBRI found that extraction of juice from water hyacinth with the beater machine was a tedious and time consuming job. In the interests of some results rather than none, and at the expense of scientific principle, some chopped water hyacinth stem, made with an electrically driven chopping machine, was also added to the contents of the reactor in order to make up the volume. It was noted that, as a result of this last addition, the inlet to the reactor was blocked solid by the short chopped sections of plant stem. It was decided to observe whether the process of hydrolysis would reduce this blockage or not.

After about two weeks gas generation started in the reactor. The ferro-cement covers at this point proved to be unsuitable because they leaked gas. They were also found to be too heavy to handle. The ferro-cement covers were, therefore, replaced by galvanised carbon sheet-steel covers.

After about three or four more weeks, just when it was thought that flow could commence through the reactor, the great flood of September 1988 destroyed the experimental set up. It was left under three feet of flood water for about three weeks. Most of the substrate and slurry were swept out of the reactor during this period.

After the flood had passed, the residues from the previous experiment were removed from the digester by the staff of HBRI. The unit was re-charged in October 1988 using water hyacinth juice. The amount of gas generated, as before, was very low. The concentration of juice used was very dilute, at 0.33% wet weight solids, and this was taken as being the reason for this low gas productivity.

The reactor was subsequently charged with water hyacinth juice including a percentage of macerated water hyacinth fibre, together with 1% cow dung. This loading resulted in a sudden discharge of a large quantity of gas which was used in a domestic oven for cooking in a nearby experimental house within the grounds of HBRI. This supply of gas ceased after a few days. It was not possible to continue feeding the reactor as the compartments appeared blocked and no flow was observed at the outlet as feedstock was added to the inlet.

Observations made at different stages of digestion indicated blocking of the flow of the substrate at the point where it passes underneath the raised baffles. There was also blocking occurring as a result of the floating tendency of the chopped plant. The experimentation in Bangladesh conclusively demonstrated the need for suitable feedstock preparation. Whether or not the feedstock could be adequately prepared without seriously reducing the availability of readily digestible organics remained to be seen.

5.3.2 Results from work in Thailand

The initial preparation of water hyacinth led to some immediate conclusions about the methods employed in the experimental work in Thailand, targeting more specifically the areas of particular interest. The batch trials were begun at different times during the course of the month in which this experimentation was carried out. It was decided to carry out the batch trials at ambient temperature in order to determine whether or not such would be feasible. In practice this experimental work was performed in the Thai cold season when ambient temperatures occasionally drop just below 30°C and the population wrap themselves in woolly jumpers.

One particularly notable feature of the results was the apparent difference in gas production rates from similar samples seeded with the same material from the same source. Juiced water hyacinth was found to vary only marginally in COD values and it is unlikely that from one juice sample to the next there would have been a significant COD variation. The variation in gas productivity rates has, therefore, been ascribed to the quality of the seed material.

Results from batch trials

Table 5.5 records that from 34.30 kg only 14.86 kg, or 43.3% of the raw weight of the plant, is captured as juice. This means that a considerable amount of water is left with the fibre. The extent to which cells of the plant are ruptured, and the efficiency with which their organic content is transferred into juice, is not covered in detail in this thesis and will be the subject of other research efforts. There will be opportunity for greatly increasing the overall system performance in this specific area.

Table 5.5 *Conversion of raw water hyacinth to juice*

Sample description	Raw weight (kg)	% of whole plant by wt	Fibre remnant (kg)	% of total fibre by wt	Juice obtained (kg)	% of total juice by wt
Root	13.11	38.22	7.97	41.00	5.14	34.59
Stem	16.22	47.29	8.30	42.70	7.92	53.30
Leaf	4.97	14.49	3.17	16.30	1.80	12.11
Whole plant	34.3	100	19.44	100	14.86	100

COD, VS and TS of juiced water hyacinth versus pulped plant

The reduction in COD from pulped plant to juiced plant, as demonstrated in Table 5.6, was significant. Root juice experienced a 77% reduction in COD, stem juice an 86% reduction and leaf juice an 88% reduction. Whole plant juice produced an 84% reduction. The process of extracting and separating the fibrous components out from the solubilised components significantly reduces the COD and suspended solids. The methods used for measuring COD and suspended solids (as discussed in section 4.1.1) do not differentiate between those organics which will contribute to the process of high-rate anaerobic digestion and those that will not contribute. As referred to in Chapter 4, the soluble fraction in water hyacinth is approximately 20%. This may be increased to approximately 40% by the use of a 1% caustic soda solution to the pre-processing of the feed. Evaluation of a 1% caustic soda solution for increasing solubility was not included within the current trials. The COD, at around 15% for juiced whole plant, is, therefore, representative of the soluble solids within the water hyacinth plant. The leaf juice, from the sample taken, shows a conversion of 12.3% from pulp to juice. In practice, however, the juiced leaf COD varied greatly, as a result of the nature of the substrate and the method of extracting the juice. The leaf is clearly demonstrated as having the highest proportion of COD with the root second and the stem the last. In practice, however, the leaf only contributes 12% of the total, whilst the root is 34% and the stem 53% (Table 5.5).

The percentage of matter as suspended solids in juice is very low, being to the order of 0.5% (Table 5.7). This compares with a dry weight percentage in raw plant of approximately 5%. By comparison the total solids represent 2.3% and the transfer from pulp to juice is in the region of 32% (Table 5.8). The transfer from raw plant to juice has, therefore, resulted in 80% of the solids being transferred as soluble solids.

Table 5.6 *COD (mg/l) of various fractions of water hyacinth as pulp and as juice.*

Sample description	*First test*	*Second test*	*Average*	*Ratio to whole plant juice*
Root juice	13,400	13,100	13,250	1.18
Stem juice	8,850	8,750	8,800	0.79
Leaf juice	16,100	15,900	16,000	1.43
Whole plant juice	11,300	11,120	11,210	1.00
Seed material	2,100	2,000	2,050	0.18
Root pulp	57,230	57,218	57,224	5.10
Stem pulp	63,000	62,500	62,750	5.60
Leaf pulp	132,000	129,000	130,000	11.60
Whole plant pulp	70,790	70,120	70,455	6.29

Table 5.7 *Suspended solids (mg/l) of various fractions of water hyacinth as juice.*

Sample description	*First test*	*Second test*	*Average*	*Ratio to whole plant juice*
Root juice	5,760	5,560	5,660	1.23
Stem juice	3,580	3,420	3,500	0.76
Leaf juice	6,260	6,380	6,320	1.38
Whole plant juice	4,660	4,520	4,590	1.00
Seed	292	250	271	0.06

The measure of volatile solids from whole plant pulp to whole plant juice is also in the region of 30% (Table 5.9). In the samples taken for this analysis the conversion of the leaf pulp to leaf juice resulted in a much greater passage of organic components than was the case in the samples taken for the analysis contained in Table 5.6. Table 5.10 summarises the rates of transfer for COD, VS and TS from whole plant pulp to whole plant juice. TS and VS are comparable in percent terms, whereas COD is approximately 50% of these two measures. This would tend to imply that the process of juicing has brought with it a significant non-digestible component.

Table 5.8 *Total solids (mg/l) of various fractions of water hyacinth as pulp and as juice.*

Sample description	*First test*	*Second test*	*Average*	*Ratio to whole plant juice*
Root juice	21,026	21,991	21,491	0.93
Stem juice	14,040	14,480	14,260	0.62
Leaf juice	66,167	66,053	66,113	2.87
Whole plant juice	22,769	23,324	23,047	1.00
Whole plant pulp	71,927	72,383	72,155	3.13

Table 5.9 *Volatile solids (mg/l) of various fractions of water hyacinth as pulp and as juice.*

Sample description	*First test*	*Second test*	*Average*	*Ratio to whole plant juice*
Root juice	11,948	12,191	12,070	0.76
Stem juice	6,024	6,128	6,096	0.38
Leaf juice	73,920	65,826	69,873	4.40
Whole plant juice	16,295	15,455	15,875	1.00
Whole plant pulp	56,046	56,287	56,158	3.54

Table 5.10 *Comparison of COD, VS and TS between whole plant pulp and juice*

Feedstock condition	COD mg/l	ratio	VS mg/l	ratio	TS mg/l	ratio
Juice	11,210	1	15,875	1	23,047	1
Pulp	70,455	6.29	56,158	3.54	72,155	3.13

Digestibility of juiced leaf, stem and root portions.

In order to arrive at a comparative estimate of the available gas production from juiced root, leaf and stem portions, a number of three litre vessels that were set up as batch reactors. These were operated at ambient temperature over varying periods of time and figures of gas production versus time and total gas production were obtained. Running parallel to the batch reactors providing information on juiced substrate a number of pulp based batch reactors were set up. Nineteen batch reactors, all with a volume of 3,300 ml, were started at different times. The contents of these are listed in Table 5.11. The four seed reactors were run in order to estimate the gas production from seed material in each of the other reactors.

Root

Figures 5.2 to 5.4 are graphical representations of some of the key trends that emerged from the batch digestion of juiced water hyacinth root. As Figure 5.2 shows, the quantities of gas produced by the pulped, as opposed to juiced, root were significantly greater. This is similarly reflected in the cumulative gas production in terms of litres per litre of digester volume, as indicated in Figure 5.3. By contrast, however, the production of biogas in terms of litre per kg of COD (Figure 5.4) shows the pulped sample to be comparable with the juiced samples. This confirms that the gas production is proportional to the organic content of the sample, as is measured by the COD test and is not reduced by the fact these have been diluted in the juicing process. Increasing the COD transfer from juice to pulp will, therefore, increase gas production.

The volume of gas produced per day, as indicated in Figures 5.2 is extremely varied. Samples 1 and 2 go negative after about 12 - 13 days, which results from the fact that the proportion of gas being produced by the seed is greater than the total gas being produced by the single reactor.

Table 5.11 *Batch reactor contents.*

Sample No.	Substrate	Dry weight (%)*	Vol of substrate (ml)	COD (mg/l)	VS (mg/l)	Seed No.	Vol seed (ml)
R1	Root juice	2.15	2,640	13,250	12,070	1	660
R2	Root juice	2.15	2,500	13,250	12,070	1	800
R3	Root juice	2.05	2,640	12,900	11,500	2	660
R4	Root juice	1.68	2,640	13,012	9,456	3	660
RPulp	Root pulp	7.88	2,750	58,244	44,256	4	550
ST1	Stem juice	0.99	2,640	8,800	6,096	1	660
ST2	Stem juice	0.99	2,640	8,800	6,096	1	660
ST3	Stem juice	0.99	2,640	8,800	6,096	1	660
ST4	Stem juice	1.41	2,100	9,460	8,720	3	1,200
STPulp	Stem pulp	8.09	2,980	61,450	49,950	4	320
L1	Leaf juice	1.88	1,800	21,435	18,750	1	1,500
L2	Leaf juice	2.27	2,640	24,300	22,730	2	660
L3	Leaf juice	1.95	2,100	22,435	19,455	3	1,200
LPulp	Leaf pulp	12.05	2,600	143,340	120,525	4	700
WP1	Whole plant juice	1.87	2,640	13,675	12,875	4	660
SE1	Seed 1	-	3,300	2,055	-	-	-
SE2	Seed 2	-	3,300	5,405	-	-	-
SE3	Seed 3	-	3,300	9,456	-	-	-
SE4	Seed 4	-	3,300	7,783	-	-	-

* *Calculated from volatile solids*

Sample 1 does not follow the trend of Samples 2 and 3. After about 18 days there is a second phase of gas production which is greater that the initial productivity.

BATCH DIGESTER : BIOGAS PRODUCTIVITY FROM WH ROOT JUICE

Fig 5.2 Corrected daily gas production per litre of digester

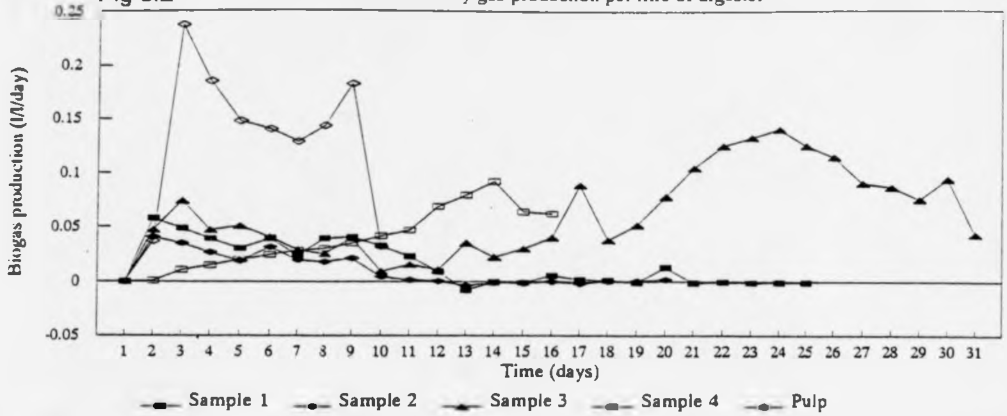


Fig 5.3 Corrected cumulative gas production per litre of digester

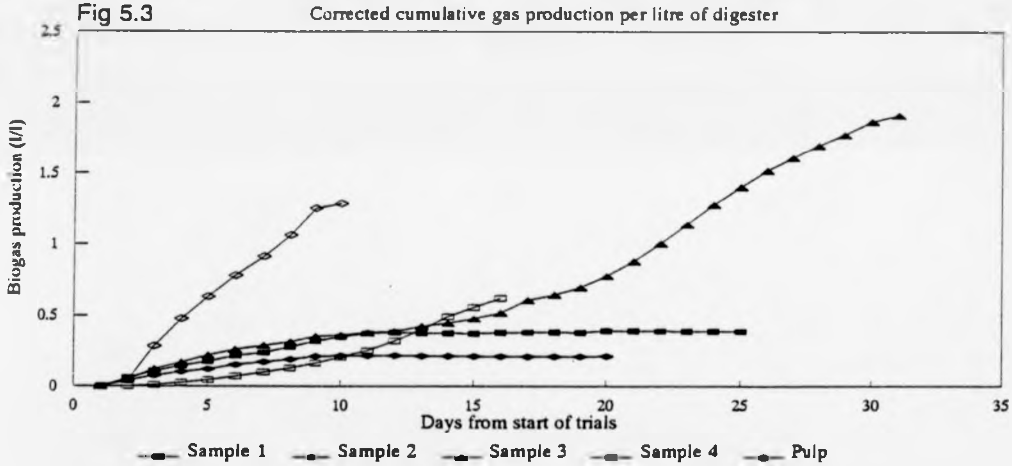
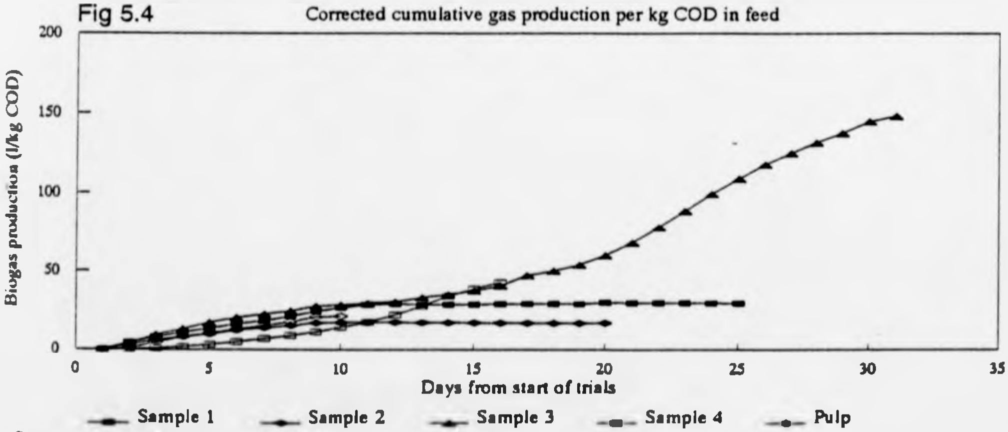


Fig 5.4 Corrected cumulative gas production per kg COD in feed



Corrected gas production = actual gas production less production from seed
Batch digester volume = 3.3 litre

It would appear that Samples 1 and 2 have encountered some difficulty in reacting properly, probably as a result of the poor seed quality. It is also possible that these batches were prepared with chlorinated water from the mains by the technician who, in the early stages, did not realise the need to use stream water when flushing out equipment.

Stem

Figures 5.5 to 5.8 provide the results from the batch reactors running on stem juice. As with root juice the trends are approximately in line with the COD of the substrate. Sample 1 appears to accelerate after 5 days and may be taken to indicate the gas productivity that could be achieved in a system where all parameters are optimised.

In simple terms of litre per litre of reactor volume (Figure 5.6) the pulp is more productive than the juice, especially in the first day. After this initial flush the gas productivity of the pulp fell back to levels comparable with juice. On a daily gas productivity basis, it is interesting to note the peak achieved by Sample 1. For the purposes of high-rate digestion this peak would come too late to be of any practical significance.

Leaf

As with root and stem, the productivity from leaf juice and pulp follows similar lines (Figures 5.9 to 5.11). The gas production per unit COD is similar for both juice and pulp (Figure 5.10) In terms of volumes of gas produced per volume of digester, the pulped water hyacinth is markedly more productive. The first days are particularly productive for leaf pulp which is extremely relevant when investigating high-rate digestion.

Comparative biogas productivity

A single juiced whole plant sample was run in a batch digester for 10 days. As can be seen from figures 5.10 and 5.11, the gas production from the whole plant juice actually outperforms the separated fractions of water hyacinth, both in terms of litres of biogas per litre of digester volume and litres of biogas per kg of COD.

Fig 5.5 Corrected cumulative gas production per litre of digester volume

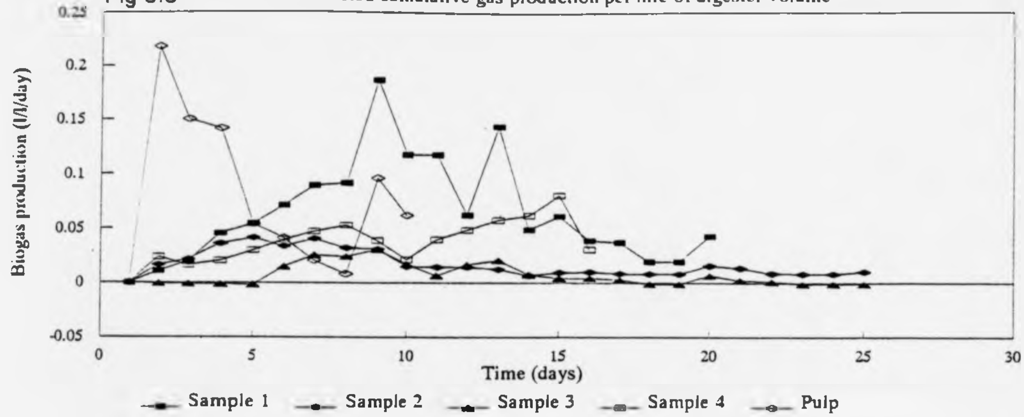


Fig 5.6 Corrected cumulative gas production per litre of digester volume

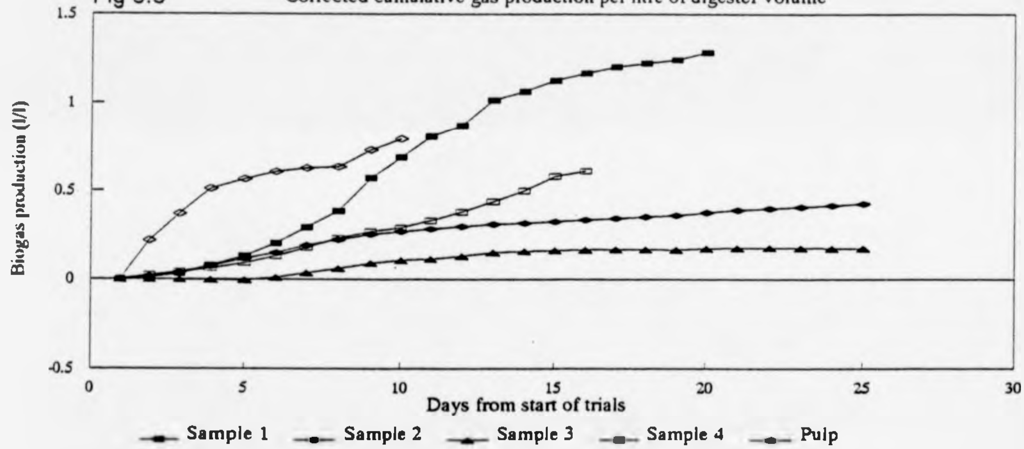
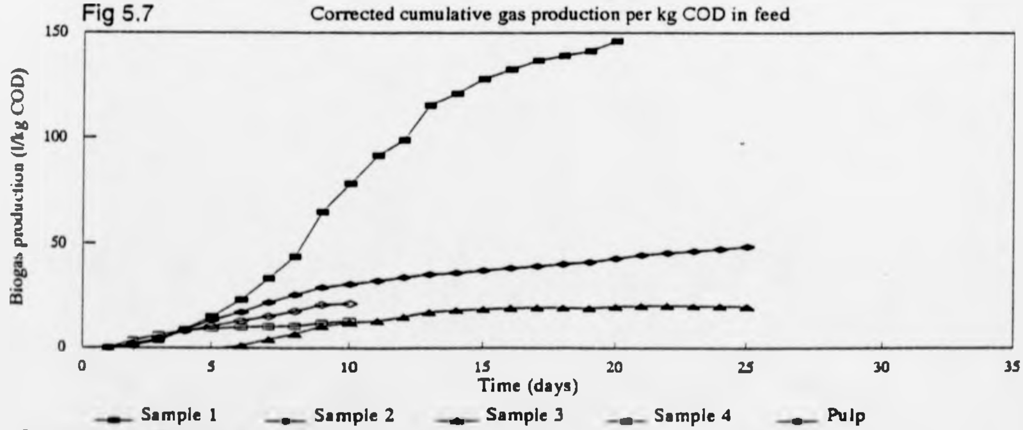


Fig 5.7 Corrected cumulative gas production per kg COD in feed



Corrected gas production = actual gas production less production from seed
Batch digester volume = 3.3 litres

BATCH DIGESTER : BIOGAS PRODUCTIVITY FROM WH LEAF JUICE

Fig 5.8 Corrected daily gas production per litre of digester

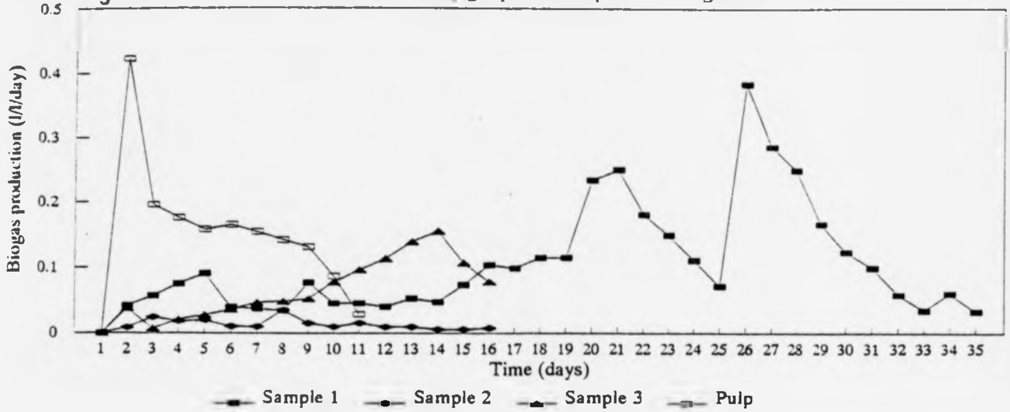


Fig 5.9 Corrected cumulative gas production per litre of digester volume

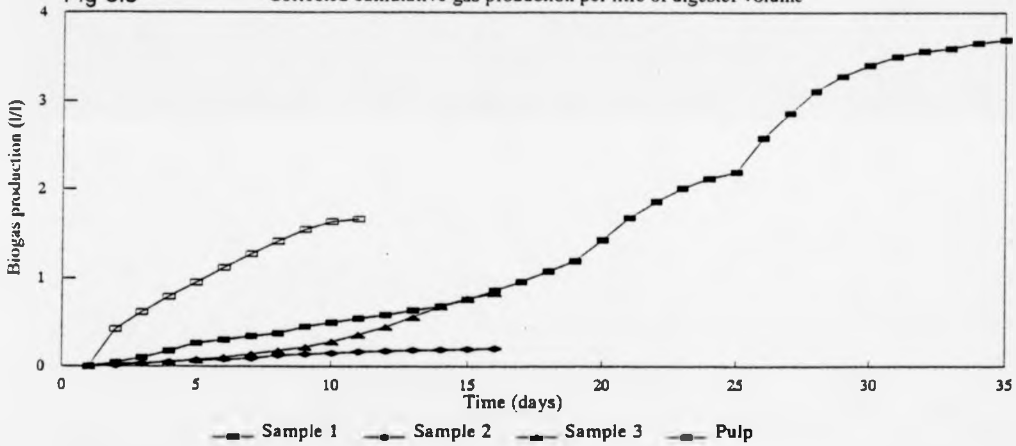
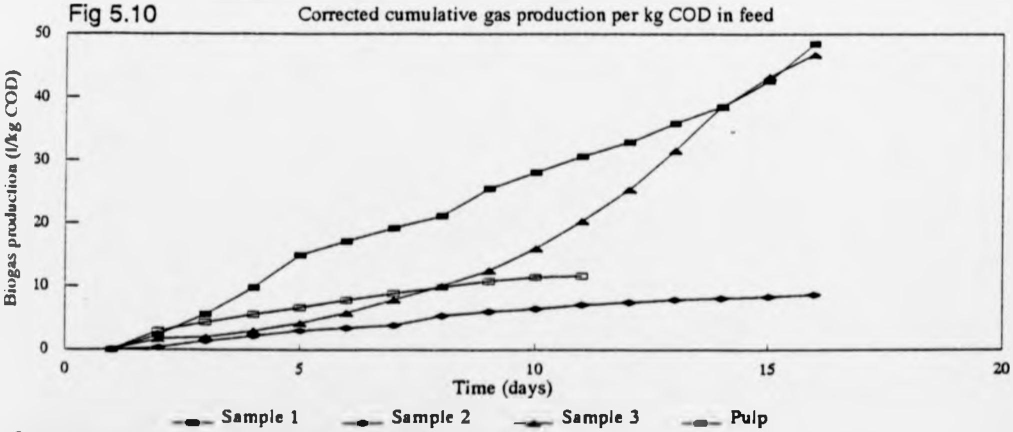


Fig 5.10 Corrected cumulative gas production per kg COD in feed



Corrected gas production = actual gas production less production from seed
Batch digester volume = 3.3 litres

BATCH DIGESTER : BIOGAS PRODUCTIVITY FROM WH JUICE

Fig 5.11 Corrected cumulative gas production per litre of digester

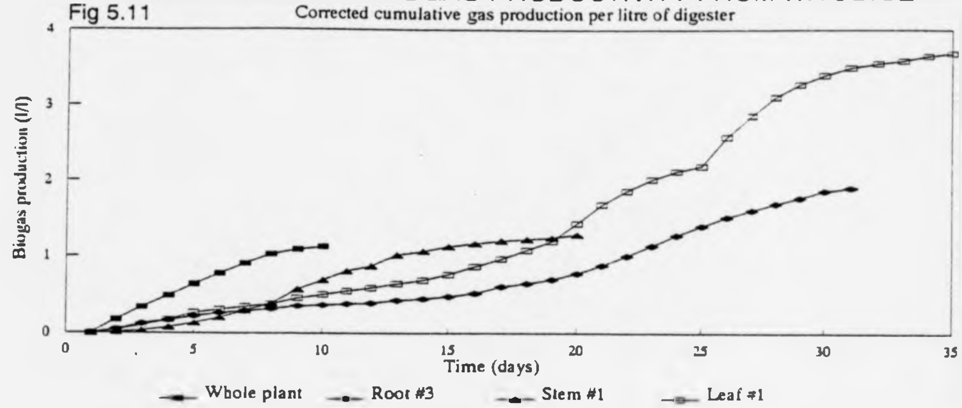
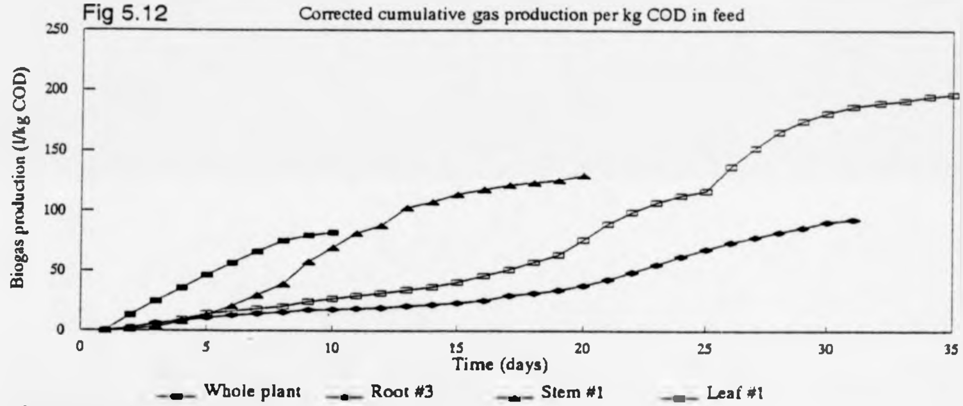


Fig 5.12 Corrected cumulative gas production per kg COD in feed



Corrected gas production = actual gas production less production from seed
Btach digester volume = 3.3 litres

Energy consumption in juicing

The nature of the experimentation precluded the accurate analysis of the total energy required for the juicing process. In reality a juicing system would involve mechanised pressing as well as mechanised pulping. The system that was finally adopted for the production of juice within this experimental programme, employed a mechanical pulping process and a manual pressing process. For this reason the estimation of energy requirements is indicative rather than precise. The pulping process involved a belt driven mincer. The bearings of the mincer were not designed for maximum power transfer and the whole machine would have benefited substantially from a refit with better quality components. It is interesting to note that the unloaded runs, the second of which was carried out after the unit had been juicing water hyacinth, had differing energy requirements. This is probably as a result of the lubrication that the machine received during its first run.

Table 5.12 *Energy consumption in slurrying whole water hyacinth plant with a mincing machine over a fixed period of 2 hours.*

Operational condition	*Energy used in first run (kJ)*	*Product juice (kg)*	*Energy used in second run (kJ)*	*Product juice (kg)*	*Average energy per kg of juice (kJ)*
Free running	*529*	*nil*	*492*	*nil*	*-*
Slurrying	*2,025*	*9.84*	*1,945*	*10.45*	*145.5*

In order to establish the energy requirement for pulping the mincer was run in an unloaded condition. The level of power absorbed within the motor was determined by means of a watt-meter measuring the total power absorbed over a period of time. A measured quantity of water hyacinth feed was then prepared and juiced, again, over a measured period of time. The juicing process was carried out slower than would have normally been the case in order to ensure that the mincer did not block and jam up. The total feedstock juiced during the fixed time period was then obtained by measuring the remnant. The quantity of juice produced was measured on a weight basis. This can be converted directly into a volume because of the low solids content. The power absorbed in pulping was compared with the power absorbed in the unloaded state. From this figure it was possible to derive an estimate of the power consumption for the pulping stage of the juicing process. (Table 5.12)

A manual press is not a satisfactory method for extracting juice on a continuous basis. By experience, the layers of pulp that might be pressed at any one time to obtain maximum juice were to the order of one centimetre. With a minimum travel of three-hundred and thirty centimetres, it meant that there was considerable effort expended in raising and lowering the plate in order to provide one centimetre of compression. Whilst the mincing mechanism adopted holds great potential for pulping water hyacinth an alternative method will be required for separating the juice and solid components. There are many proprietary pieces of equipment for dewatering slurry. These will not be discussed in this thesis.

5.4 DISCUSSION OF RESULTS FROM INITIAL EXPERIMENTATION

Despite the numerous problems encountered, useful data was obtained with which to continue the assessment of the proposed process route. This is discussed below.

5.4.1 Bangladesh

Solubilisation

The periods of time involved with the solubilisation of machine chopped and hand chopped water hyacinth indicate the problem with regard to high-rate anaerobic digestion. In reality there is very little difference between the hand-chopped and the machine-chopped samples as presented in Table 5.1. The former were in general, longer, whilst the latter were more evenly cut. The initial total suspended matter and the total dissolved matter reflected the amount of chopping that had gone into producing the feedstock. After about seven days digestion appears to have commenced, reducing the suspended and dissolved matter levels within all samples. The concentrations of suspended matter and dissolved matter, as a function of dry weight, were calculated from the results and are shown in Table 5.13. For the purpose of this interpretation a figure of 5% dry weight solids in the plant was assumed. The actual figure was not recorded but the approximation will serve the current requirement to estimate the approximate quantities of dry matter that may be expected to pass into solution.

Table 5.13 indicates that there is considerable promise for a high-rate digestion process relying on matter passing into solution. The combination of soluble and suspended matter approaches 80%, of the assumed dry weight, after three days in the case of machine chopped plant matter. The use of a 5% dry weight assumption will possibly have pushed this percentage up but the general conclusion is favourable.

The addition of 2% cow dung had a significant impact upon the total suspended matter but created little change in the total dissolved matter. (Table 5.2) The increase in suspended matter is probably as a result of the cow dung itself, whereas the small change in dissolved matter until day 10 suggests that such additions will not assist the process of solubilisation for the preparation of a high-rate digestion feedstock.

Pre-digestion

The figures for gas generation from pre-digested water hyacinth indicate that the use of pre-digestion may be an acceptable method for pre-treating water hyacinth (Table 5.3). This aspect is taken no further within the current work, other than noting its potential application. It may be that in a full-scale scheme a certain amount of predigestion can be beneficial by buffering the feed into the reactor for a number of days. It is interesting to note that the maximum gas generation was obtained during the period seven to fourteen days from commencement of digestion. This is more rapid that one would normally expect for a batch reactor with water hyacinth as a feedstock. The maximum rate of gas generation attained was 1.38 litres biogas per litre digester volume per day, which is significantly greater than the rate of gas generation from the batch trials produced in Thailand.

Table 5.13 *Percent total suspended matter (TSM) and total dissolved matter (TDM) as a function of dry weight.(Dry wt taken as 5% wet wt.)*

	% TSM Duration in Days				% TDM Duration in Days			
Process	0	3	7	10	0	3	7	10
Hand chopped (aerobic)	12.4	24.2	34.0	38.6	11.9	34.0	46.0	27.6
Hand chopped (anaerobic)	12.4	23.1	32.6	26.7	11.9	34.0	29.8	25.2
Machine chopped (aerobic)	25.0	34.3	41.6	37.9	19.6	45.0	32.8	38.2
Machine chopped (anaerobic)	25.0	28.2	43.8	32.1	19.6	48.8	31.8	31.5

The weight loss recorded for different arrangements of chopped water hyacinth demonstrate conclusively the need to pre-process the raw water hyacinth if high-rate anaerobic digestion is to be achieved in practice.(Table 5.4)

The difficulties experienced with the multi-stage upflow reactor in Dhaka, combined with the positive indications from the laboratory work, lead to the conclusion that greater emphasis should be placed upon the method of pre-treatment prior to charging such a reactor for the purposes of high-rate digestion. It was also decided, as a result of the work in Dhaka, that it would be advantageous to return to laboratory-sized digesters and to run several different reactors at the same time.

5.4.2 Thailand

Following on from the work in Bangladesh, the initial work in Thailand investigated various methods of juicing water hyacinth. The conversion of raw-weight plant matter into raw juice resulted in a reduction in weight of approximately 57%. (Table 5.5) The loss in COD was even more marked, being approximately 84%. (Table 5.6) The losses in total solids and volatile solids were 68% and 72% respectively.

In view of the promising initial figures obtained in Bangladesh, the comparatively low conversion from raw plant matter to juice was recognised as being a function of the juicing method and not a fundamental obstacle to the system concept. The weak link in the juicing arrangement in Bangkok was the pressing of liquid from the pulped biomass. Where considerable care was exercised in pressing with the screw press greater quantities of juice could be obtained. The use of 1 cm layers in the press was probably excessive. The need, however, was to produce juice on a semi-continuous basis in order to run the research reactors. It was, therefore, taken as a basic outstanding factor that the method of separating juice from slurried biomass should be improved prior to further development work on the system as a whole. The use of a mechanised press, applying a greater force and on thinner layers was assumed to be necessary in order to approach the levels of suspended matter and dissolved matter obtained in Dhaka with a process of maceration. (Table 5.13) A machine was not located that would have fallen within the budget of the current project.

Following the outcome of the initial pilot plant trials in Bangladesh, where severe blocking of the flow paths had obstructed continuous operation of the reactor, it was necessary to determine at a rudimentary level that high-rate digestion with juice would be feasible and, further, to arrive at an indication of the gross operating characteristics of a system based upon this premise. The use of the juice produced by the mincer and hand-press served this purpose.

With regard to the energy requirement in juicing (Table 5.12), the energy required for pulping was approximately 145 kJ per kg of juice produced, or 337 kJ per wet kg of water hyacinth and 6.740 kJ per kg dry weight, assuming a 5% solids content. With a maximum gas production potential of 280 litres methane per kg dry weight, this represents 69% of the energy production potential. Whilst this is a high figure it is not meant to be representative of the efficiency that might be achieved with industrial machinery. The objective here, as stated above, was not be study the efficiency of juicing but rather the feasibility of high-rate digestion with juiced biomass.

Batch trials

Perhaps the most significant observation to come out of the batch trials is that there appears to be little advantage in separating the leaf, stem and root in a process where juicing or pulping is to be employed in feedstock preparation. All samples performed approximately in relation to their organic content.

An important aspect is the amount of organic material that is passed from pulp into juice. Where the gas productivity is proportional to the organic content it is optimal to maximise the latter in the substrate fed to the reactor. This productivity must be set off against the facility with which the organic content is converted to gas. There is no doubt that if the technique to be employed were batch digestion, the optimum would be to feed the pulp into the digester and save the costs associated with separation. There is some argument to indicate that the fibre would be a better quality after the anaerobic bacteria have removed the readily biodegradable organics and that separation of the fibre would be made easier by the digestion process.

5.5 ISSUES SELECTED FOR FURTHER INVESTIGATION

To build upon the previous work and develop a methodology, specific variables were selected for particular attention in the operation of the continuous anaerobic digesters.

5.5.1 Operation of the multi-stage upflow reactor with inclined weir plates.

As a consequence of the work in Bangladesh and initial experiments in Thailand, it was decided to investigate further the operation of the multi-stage upflow reactor with inclined weir plates (IWR). The severity of the problem of blocking within the multi-stage upflow reactor was an unforeseen obstacle to the implementation of the proposed high-rate anaerobic digestion system with juiced water hyacinth.

5.5.2 Operation of the process with different portions of water hyacinth.

Included within the assessment of the operation of an IWR was the relative performance of the different components within the water hyacinth. The separate consideration of root, stem and leaf was intended to highlight whether any one particular component should be removed prior to the juicing process.

5.5.3 Ambient temperature operation.

As mentioned in section 5.4.2, the desirability of operating the reactor at ambient temperature results from savings that can be made on capital costs and energy output. Where the plant requires heat-exchangers and process heating, the overall efficiency of the system will be reduced. It was decided to operate all the experimental high-rate reactors at ambient temperature to determine whether any fundamental operational difficulties would be encountered.

5.6 DESIGN OF THE EXPERIMENTAL REACTOR

A number of factors were considered in detail for the design of the continuous upflow anaerobic reactor for use with juiced water hyacinth. Primary amongst the issues addressed was that of the blocking of the reactor baffles.

5.6.1 Selection of loading rate.

There are a number of factors which are affected by the system flow rate. For example, if the flow rate is reduced and the retention time increased, the percentage reduction in volatile solids will be increased. Within the structure of the water hyacinth plant there are soluble solids which will be more readily anaerobically digested than other less soluble solids. This spectrum of solubility spreads through to cellulosic and ligno-cellulosic substances which will be highly refractory and only reduced after an extended period of time allowed for solubilisation. However, as has been identified several times in this thesis, the ratio of gas production per cubic meter of installed capacity is offset by the ratio of both capital and operational costs of each cubic metre of installed capacity. The reduction in retention time versus the capital cost of the unit and the value of the output will be of critical importance in a commercial system. This optimum point of application will be one of the criteria to be resolved for each specific application.

5.6.2 Selection of operating temperature.

It is a well established fact that as the temperature of anaerobic digestion increases, from the psychrophilic through the mesophyllic to the thermophilic range, the rate of anaerobic digesting likewise increases. Set against this, however, is a similar increase in sensitivity of the bacteria to temperature change. Mesophyllic bacteria will tolerate temperature variations of ± 2°C, whereas thermophilic bacteria are tolerant to temperature changes of only ± 0.5°C. A thermophilic system, therefore, requires to be very carefully controlled.

Water hyacinth, on the other hand, is found to grow only where temperatures exceed a minimum of 20°C. In the countries where the possibility of water hyacinth utilisation was considered as part of this work, Bangladesh and Thailand, there is a minimum ambient temperature of approximately 30°C. This being the case, there is considerable benefit to be gained if the digester can reliably be operated at ambient temperature. The introduction of process heating will divert energy from the value side of the output of the system. It is for this reason that it was decided to operate all the anaerobic digesters at ambient temperature.

5.6.3 Arrangement of the reactor baffles.

This is a fundamental area which will require attention during the course of this experimental exercise and will require further consideration for full-scale installations. The current arrangement of the baffles in the multi-stage upflow reactor are only satisfactory where the substrate being fed into the reactor is fully soluble. Indeed, the multi-stage upflow reactor has been described as a reactor suitable for only soluble substrates (Grobicki, 1991).

The problem of blocking was observed early in the research work. The first multi-stage upflow reactor constructed in Bangladesh in the grounds of HBRI was unable to operate effectively because of this problem. To some extent, this initial miscalculation may have resulted from the use of terminology in describing the substrate requirements for the multi-stage upflow reactor. It is possible to have fully soluble substrates with percentage solids of 10% or more. The fact that the water hyacinth has a solids content of 5% does not, however, mean that it should function adequately within a multi-stage upflow reactor. A significant proportion of these solids are ligno-cellulosic and not amenable to the process of anaerobic digestion.

With hindsight it appears simply a matter of common sense that water hyacinth solids placed in the multi-stage upflow reactor will collect at the base of the individual chambers and will eventually block the system. This is indeed what happened with the reactor in Dhaka. Attempts at reducing the effect of solids on the operation of the reactor were not successful because the system had not been designed to allow for the possibility of blockages.

Further work in Thailand emphasised this problem. The first set of reactors constructed of perspex enabled the blocking process to be viewed. The problem with the multi-stage upflow reactor is that it presents a long slot-entrance to each of the risers within the individual chambers. With any solids content at all there is thus a possibility of differential flow gradually increasing to the point where channelling becomes pronounced and, eventually, blockages occur by virtue of the fact that solids are not being carried through. At a low flow rate, this may not be such a pronounced difficulty. With a juiced feedstock, the solids in the feed have been separated from the more refractory ligno-cellulosic constituents within the water hyacinth plant and, therefore, will eventually be reduced by the process of anaerobic decomposition. At the relatively high flow rates at which it is desirable to operate the multi-stage upflow reactor, any components which are not solubilised will remain in the flow path and eventually blocking will occur.

This situation may be compared to the upflow anaerobic sludge blanket. In this reactor arrangement, substrates with comparatively high insoluble solids loading may be used as feed. The reason that blocking does not occur here is that there is an inlet pipe with a high velocity. The action of gravity around the exit from the inlet pipe similarly causes a mixing and displacement movement on any solids that are passed into the chamber. By this means the more refractory solids are able to be retained longer within the system, whereas the more readily solubilised solids move through the system and are digested.

The arrangement of the baffles within the multi-stage upflow reactor was reconsidered, bearing in mind the empirical observations made in both Bangladesh and Thailand. By reducing the size of the entry into the baffles, the velocity at the base of each chamber may be significantly increased. This increase in velocity assists in preventing the blocking of each chamber by a similar mechanism to that employed in the upflow anaerobic sludge blanket. A further objective was to encourage recirculation above each of the riser inlets and thereby assist with the mechanisms which help to prevent blocking. In order to follow through with these principles, the initial narrow entry was gradually increased by means of inclined walls. This development was referred to as the inclined weir reactor. (See Figure 6.1)

Chapter 6.

TRIALS WITH THE INCLINED WEIR REACTOR (IWR)

This chapter discusses the development of the Inclined Weir Reactor (IWR) and presents the results of trial runs with the configuration selected. From the information obtained conclusions are drawn as to the potential for the IWR to run with water hyacinth juice and suggestions offered for its improvement.

6.1 EXPERIMENTAL APPARATUS

Development of the IWR in Bangkok began with the design of the weir plates. Their arrangement is viewed as one of the key geometric relations involved in facilitating the operation of a high-rate multi-stage upflow anaerobic digester operating with suspended solids. Solids blocking at the base of vertical plates occurred rapidly after start-up both in Bangladesh and with the first set of reactors built in Thailand. Both adequate solubilisation, achieved with adequate pre-treatment, and insoluble-solids management, by means of reactor design, are required.

Weir plate design

In order to arrive at a design velocity for the riser-chamber inlet, results were taken from settlement rate tests carried out in Thailand. (Table 6.1) These test were performed by placing shaken substrate into a graduated cylinder and observing the rate at which particles settled. The cylinders were kept undisturbed for a period of three days. In all cases the juice clarified in the top 10 mm section of the cylinders after about 10 to 15 minutes. In the case of leaf juice, the difficulty of separating the juice from the solids resulted in a thicker liquid which appeared to settle more rapidly. After 15 minutes the top 100 mm of the leaf juice sample had clarified leaving a brown/grey liquid.

After three days the *stem* settled to an 11 mm deep solids layer in the base of the cylinder with a light-green liquid filling the remainder of the cylinder. The *leaf* settled into a 28 mm deep solids layer in the base of the cylinder and a floating 28 mm solids layer in the top of the cylinder. The *root* formed a 10 mm floating layer in the top of the cylinder, another floating layer, 40 mm thick, approximately half-way up the cylinder and no bottom layer. The material from both the root and the leaf appeared to have flocculated whereas that of the stem retained a silty appearance.

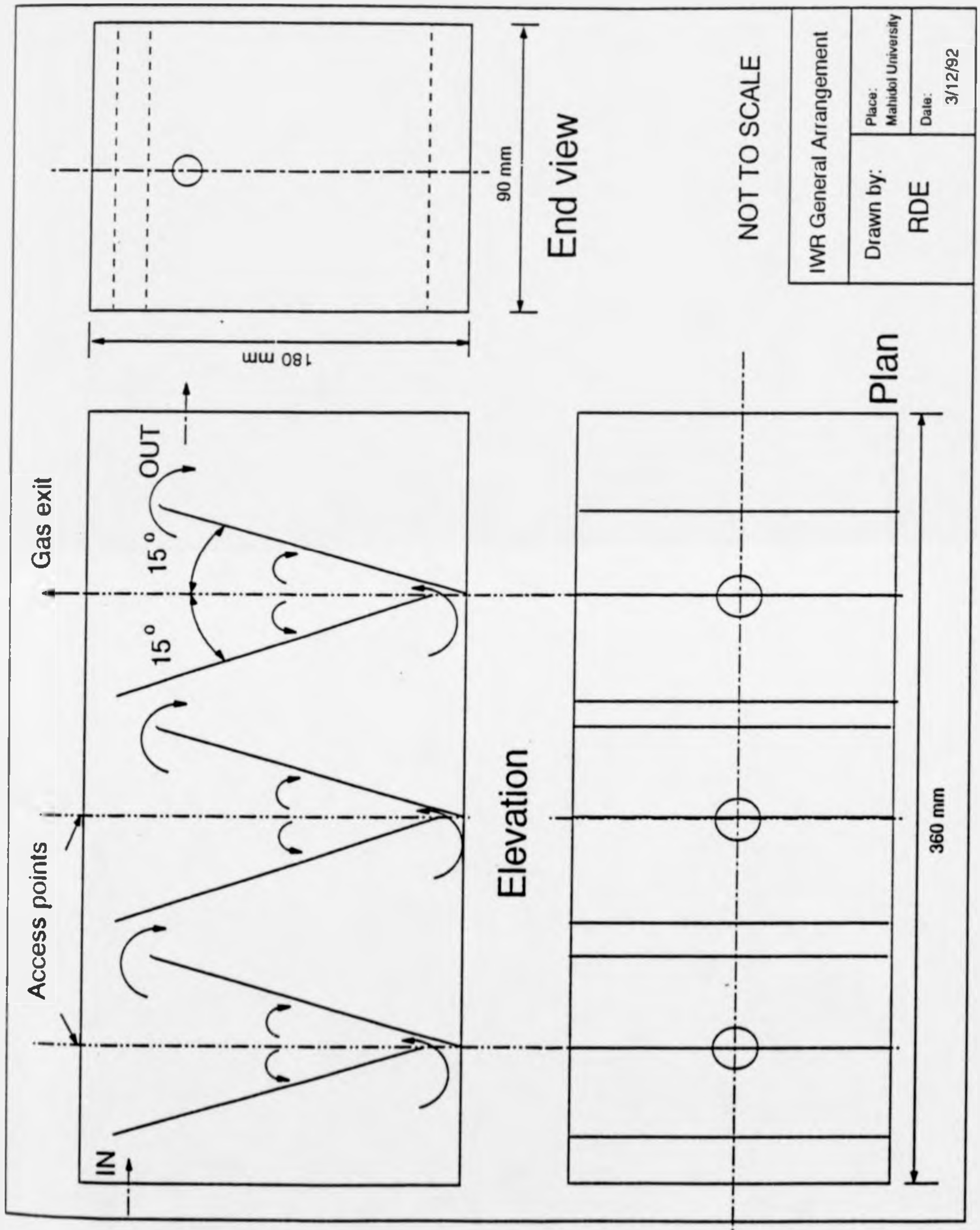

Access points
Gas exit
IN
OUT
15 °
15 °
Elevation
Plan
360 mm
180 mm
90 mm
End view
NOT TO SCALE
IWR General Arrangement
Drawn by:
RDE
Place:
Mahidol University
Date:
3/12/92

Figure 6.1

The tendency to float or sink is one of the key problems with water hyacinth in anaerobic digesters. In batch reactors, with retention times of up to forty days, it is necessary to find ways of holding the floating mat below the surface to ensure that digestion will proceed. The three-day stratified material was shaken up manually by inverting the graduated cylinder and the solids immediately returned to their original state, distributed evenly throughout the cylinder. This would indicate that in a multi-stage upflow reactor, with comparatively high liquid velocities at the points of potential settlement, the plant material will not settle out and will be carried through the reactor, as is necessary for satisfactory operation.

Table 6.1 Settlement velocity of various preparations of water hyacinth.

Biomass preparation	Maximum settling velocity (m/sec)
Root juice	2.5×10^{-4}
Stem juice	2×10^{-4}
Leaf juice	1.25×10^{-4}
Whole plant juice	1.75×10^{-4}

A design value of 1.2×10^{-4} m/sec was selected for the velocity in the base of the riser, with an hydraulic retention time of twenty-four hours in the reactor as a whole. The angle of inclination was chosen as 30°. This provides a gradually reducing velocity up to the overflow section and into the next chamber. (See Figure 6.1.)

Experimental reactor design

For this final set of trials, the volume of the digester was once again reduced, from that of the Bangladesh trials and the initial Thai trials, in order to facilitate the study of the blocking aspect of the reactor operation. A further reason for reducing the size of the reactor was of a practical nature. With larger reactors built previously in the laboratory in Thailand it was discovered that leaks occurred both through the seals on the lid and, occasionally, through the joints between the wetted walls. One or two catastrophic leaks had resulted in the complete loss of the liquid portion of the substrate. This was the result of the an inadequate construction method, combined with the use of poor chloroform glue, used to fix the perspex structure together. A metal frame was welded together, around the perspex vessels, in an attempt to hold the walls in place but this had had limited effect in stopping corner-joint leaks. The use of a smaller reactor volume was intended to place less stress on the joints of the reactor walls.

The lid of the reactor was perforated with holes for exit of gas and to facilitate any stirring that might be required to dislodge blocks to the flow of the substrate. The holes were filled with black rubber bungs.

Harvesting

Harvesting of water hyacinth was carried out on a daily basis from the local university ponds which were amply stocked with water hyacinth. There was a minor setback which resulted from the King's birthday. It appears that there is a tradition in Thailand to clear aquatic weeds from waterways on this particular date. The regular source of water hyacinth for the experimentation was collected by the university authorities and students and deposited on an adjacent bank to rot. Fortunately, a pond was found outside of the university grounds where this custom had not been adequately implemented and feedstock was collected from this source. Within a matter of four or five days the water hyacinth plant had returned to the original pond, in adequate quantities for harvesting to resume as normal.

Juice preparation

As with previous experimentation, the juice was prepared by means of a motorised mincer and a manual screw press. In order to input juice into the IWR, a feed-hopper arrangement was constructed with a peristaltic pump drawing liquid from the hopper and passing it through the IWR.

During the weekend and over extended periods of restricted access, such as Thai public holidays, adequate juice was prepared to run the reactor through the period and gas production levels were extrapolated from prior and subsequent data. A factor which influenced the satisfactory operation of the reactors was the tendency of the substrate to separate out into solid and liquid portions. During periods of attendance it was possible to occasionally stir the feedstock but during absences of several days, upon return, it was found that the solids had moved into various positions which made it difficult for the reactor to attain steady-state conditions. This is believed to be one of the contributing factors to the unstable operation of the reactors. It is clear that the digesters will require regular supervision if operated in their current form.

Gas flow rate measurement

On the liquid exit-port, in the end wall of each IWR, a manually arranged liquid seal was installed which could be adjusted to account for differences in pressure within the reactor. The gas exit-port was located in the top of the IWR. The measurement of gas flow rate was achieved by means of a displacement arrangement. As gas pressure built up within the reactor, water was displaced from a water filled jar into a measuring cylinder. Much difficulty was experienced in balancing this system at the commencement of this final experiment, and various alternatives were attempted, such as an inverted jar to prevent pressure being placed upon the reactor. After some juggling with the various liquid seals and vessels involved it was possible to set the pressure balances in the range of gas production and thereby collect the product gases in the correct vessel and not lose them through the liquid exit port, as happened occasionally at the beginning of the experiment. It remained, however, necessary to do "spot-sampling" of gas production rates by recording the amount of gas production over a given period. All readings, therefore, are based upon short-term readings extrapolated over a 24 hour period. As methane is virtually insoluble in water the possibility of readings being effected by this means was insignificant.

Sample analysis

Samples for analysis from the IWR were collected on a daily basis by technicians from the Department of the Environmental Sciences. To commence with, a range of different parameters were analyzed but as the experiments progressed it became clear that COD analysis alone would be adequate. From this parameter the remaining parameters of interest, such as suspended solids and volatile solids, could be deduced with an accuracy commensurate with that of the overall experiment.

The COD of the various components was found to vary, at times significantly. In the case of leaf juice, this resulted from a low fibrous content and a comparatively high soluble solids component. The initially high COD of the leaf was reduced by varying degrees, depending upon how the juice was pressed in the screw-press. Inadequate attention to separation and layering occasionally resulted in significant quantities of solids passing through the screw-press holes. The fact that leaf juice was only approximately 12% of the whole plant meant that there was an incentive for the person collecting and pressing the feedstock to be less scrupulous in the screw-press operation. In the case of stem and root, the fibrous component formed a mat over the holes and acted as a filter to the passage of substantial quantities of solid material. In the case of the leaf the low fibre content resulted in the holes being inadequately filtered. This inadvertent collection of solids within the leaf juice passed into the IWR running on leaf juice. Blocking of this unit was more commonly encountered than that of the

IWR's running on stem, root and whole plant juice.

6.2 EXPERIMENTAL METHODS AND PROCEDURES

It is the nature of carrying out experimentation in developing countries, with a limited budget, that facilities tend to be rather rudimentary. In the case of Mahidol University, the setup was better than one might have reasonably expected. An area of approximately six metres by six metres was provided for the research equipment. This was located in a ground floor of an outbuilding to the Department of Environmental Sciences. Two minutes walk from this building there was an internal university pond where water hyacinth was growing abundantly. The problem of harvesting was completely resolved in this location. The electricity supply in Thailand is 415 volts, three phase, 50 Hz, which meant that apparatus purchased in England was able to function accurately.

Feedstock preparation

Water hyacinth was manually harvested from the university pond. By experience, approximately 40 kgs of water hyacinth produced approximately 20 litres of juice, which was the daily requirement for four reactors. Because of the bulky nature of the plant, the number of trips made to carry water hyacinth into the laboratory was considered to be excessive. Attempts were made at chopping the harvested plant at source and loading the bucket more compactly. In practice this was found to slow down the proceedings as the feedstock was double-handled for separation. Harvested whole plant was, therefore, brought from the university pond into the laboratory. The plant was separated into its root, stem and leaf portions ready for slurrying in the mincer. The stem and root sections required to be cut into smaller dimensions in order to fit into the inlet orifice of the mincing machine. Once so prepared the buckets were weighed to record the mass of fresh water hyacinth entering into the juicing process. Juicing then began. With concentration and effort it was possible to juice approximately 10 kgs per hour. This meant that the harvesting and juicing for 40 kgs per day was a full time activity. The laboratory technician initially assigned to this duty was not able to devote the necessary full time effort required and an assistant was employed for the period of the research programme to carry out both the harvesting and the juicing operation. No attempt is made here to justify the efficiency of the experimental system. Its prime requirement was to be functional. It is certain that if a larger mincing machine had been purchased, and if the pressing process had been mechanised, it would have been possible to have a much higher throughput and possibly, therefore, not have required a full-time assistant to perform this simple function. However, the high labour requirement for preparation was itself a finding of some importance, as it feeds into the assessment of the economic viability of following the 'juicing' path to water hyacinth gasification. As the research efforts in Bangladesh had clearly demonstrated, attempts made to improve much beyond the resources and facilities readily available are usually very time consuming and frustrating.

Even within the structure of the Bangkok economy it took approximately six weeks to select a suitable mincer and an overall method of juicing. The mincing technique, despite its low throughput in this particular situation, is very promising. The calculation of the energy requirement per kg of juiced material, however, is not acceptable for a commercial system and more work will be required in this area. Once juiced the liquid was placed in the inlet feed tank ready for abstraction by the peristaltic pump and delivery to the IWR. All fittings and pipework were purchased locally. The system was, therefore, readily altered and adapted to suit particular variations. Generally, adequate feed was prepared to operate the plant for a period of twenty-four hours. In the case of weekends and public holidays the quantity of feed stored in the inlet vessel was increased. The plant was kept running during periods of absence. A further requirement was to ensure that escaping methane gas did not build up within the building. The building was well ventilated, as was necessary to overcome the absence of air conditioning, so methane build-up was not a serious problem. A vent pipe arrangement was set up to pipe gas from the reactors to the outside of the building, primarily for reasons of odour sensitivity rather than of hazard prevention.

Measurements within the experimental IWR's

Four IWR's were constructed, each with a volume of five litres. Each reactor was operated on a different substrate for a period of time. The flow rates in the reactors were kept at approximately the same level. The four substrates chosen were root juice, stem juice, leaf juice and whole plant juice. The peristaltic pumps, each with a flow control arrangement operated by means of valves and by-pass lines, were used to feed juiced bio-matter to the IWR inlet.(See Figure 6.2) Temperature was measured by means of a mercury thermometer inserted through the lid of the reactor vessel. Flow rate was measured by disconnecting the inlet feed pipe and, whilst retaining the same head on the peristaltic pump, measuring the time taken to fill a set volume within a 100 ml graduated cylinder. Adjustments were made to the valved by-pass circuit to bring the flow rate into the desired range. An attempt was made to fit a variable resistor to the DC motor on the pump, in order to control speed by changing voltage, but this proved not to be possible in view of the absence of a suitable variable-resistor.

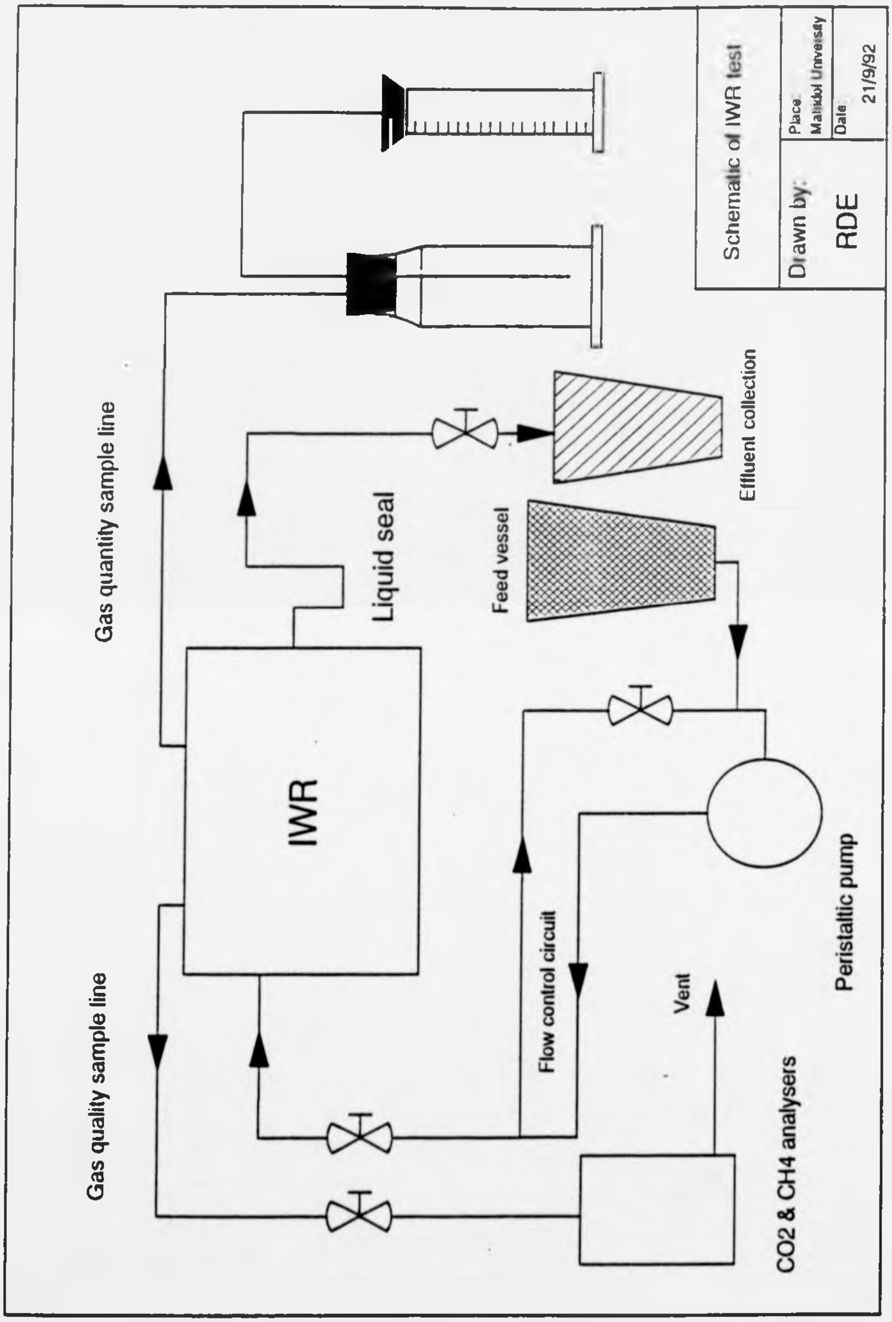

Gas quantity sample line
Gas quality sample line
Liquid seal
IWR
Feed vessel
Effluent collection
Flow control circuit
Vent
Peristaltic pump
CO2 & CH4 analysers
Schematic of IWR test
Drawn by:
RDE
Place:
Date:
21/9/92

Figure 6.2

Because of the inherent unreliability of the gas collection method greater reliance has been placed upon the COD reduction, in terms of inlet COD versus outlet COD, as a measure of reactor performance. Volatile solids were also sampled at the commencement of each run in order to establish the approximate ratio of COD to volatile solids on the inlet and outlet. It is not necessary to measure both parameters in order to assess the manner in which the operation is proceeding. Samples were taken from the influent and effluent liquid every evening and collected for analysis in the laboratory of the Department of Environmental Sciences.

Start-up procedures

All reactors were inoculated with seed material taken from a cultivated seed, developed over a number of months and adapted for use with water hyacinth juice (See section 5.2.2 *Seed material preparation*). Each reactor was filled with two litres of seed solution and three litres of feedstock. The COD removal efficiency was calculated from the difference between the influent on one day and the effluent on the following day. Where following day readings were not obtained the intermediary readings were extrapolated. The reactors were commenced with an Hydraulic Retention Time (HRT) of approximately 100 hours and this was reduced to 35 and then 24 hours over the initial period of operation. Measurements of pH were taken with litmus paper. The pH was not observed to fall below 6.5 and, therefore, no additions were required for pH buffering.

6.3 RESULTS

The primary objective of the experiment with four IWR's was to verify the performance potential for each of the components of water hyacinth on its own and in combination. The following results confirm that the IWR, with necessary modifications, can be used to digest juiced water hyacinth.

6.3.1 Method of presentation

During the period of operation of the four IWR's an enormous number of readings were taken. In order to assist with their presentation they have been entered into Lotus spreadsheets which are included in Appendix 2. By entering the data into a spreadsheet it has been possible to analyse graphically the various relationships of interest. A selection of these relationships are also included in the appendix and will be discussed in the subsequent paragraphs of this section. The relationships between COD reduction, retention time and temperature are those of particular interest.

6.3.2 Root juice

The COD removal efficiency rose rapidly over the initial period from 6% to 42% (Figures 6.3 to 6.5). This was in part associated with the lower flow rate employed in the start-up period. A lower flow rate is expected to be more effective since it gives a longer retention time. The input COD of the root juice varied around 13,500 mg/l. The system performance can be seen to be gradually improving during the period of operation. It is reasonable to consider that a more or less steady state condition had been achieved by the thirtieth day of operation. In the steady state, daily gas production was in the region of 120 litres per kg COD and 1.8 litres per litre of digester volume. This compares with the daily gas production from the batch reactor where figures for the same substrate achieved maximums of only 11 litre per kg COD and 0.11 litres per litre of digester volume. A further comparison is with the best, batch digester, cumulative thirty day figures for root juice (Sample 3) where approximately 150 litre per kg COD and 1.5 litres per litre of digester volume were obtained.

The erratic nature of the readings is the result of a number of factors. The influent COD varied according to the quality of the feed and the manner in which it was prepared. The efficiency of the process was subject to the variation in ambient temperature and, although no direct correlation is immediately apparent with the figures obtained, it is likely that a commercial system operated without temperature controls will be subject to similar variations.

The quality of the seed appears to have had no effect upon the relative performance of the various substrates employed. This may be as a result of the continual mixing present in the IWR which ensured that better contact and mass transfer occurred. It may simply have been that the bacterial variations in seed material taken for IWR runs were not significant. No facilities were available for monitoring bacterial types and concentrations during the current trials.

A maximum of 50% COD removal efficiency was attained after thirty days. This would suggest that the system was not operating to a level that has been achieved in other trials with other substrates using the method of continuous multi-stage, up-flow chambers (Grobicki, 1989). A point to note, however, is that 50% COD removal efficiency is a substantial improvement upon results obtained with this system using other forms of feedstock preparation.

CONTINUOUS IWR : BIOGAS PRODUCTIVITY FROM WH ROOT JUICE

Fig 6.3

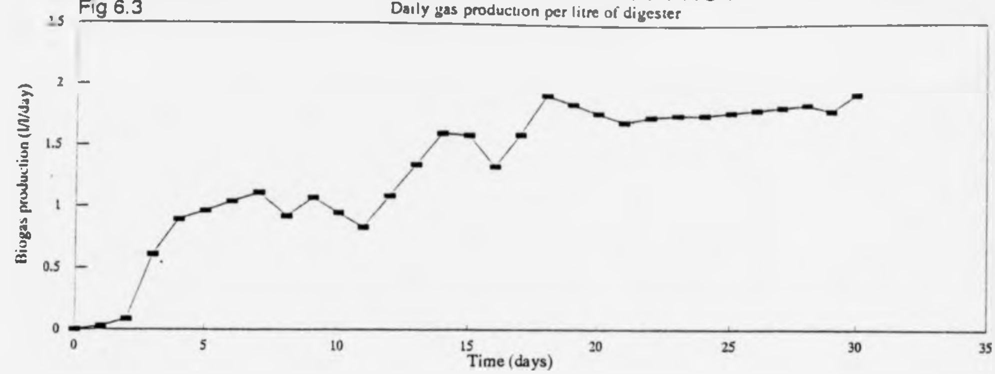


Fig 6.4

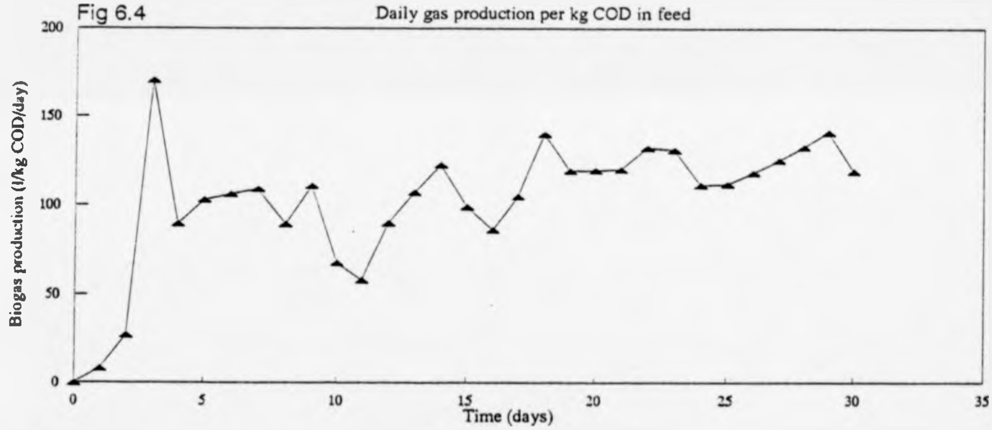
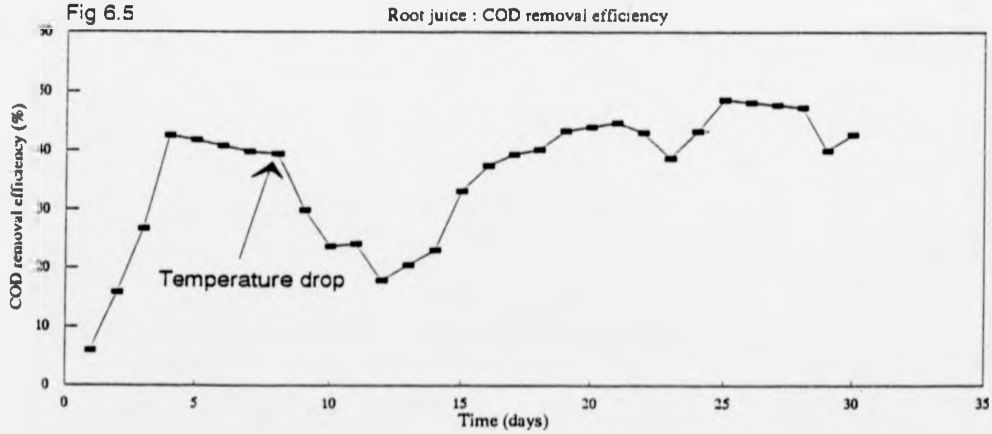


Fig 6.5



6.3.3 Stem juice

The approximate COD of the root juice substrate, the performance of which has just been described, was 9000 mg/l. This is low in comparison to the other substrates tested. As with the IWR operating on root juice, when using stem juice steady state conditions only began to appear towards the end of the experimental run. The trend, if anything, suggests that continued improvement in performance may yet have occurred. (Figures 6.6 to 6.8) The daily gas production from stem juice was in the region of 120 litres per kg COD and 1.0 litre per litre of digester volume. Whilst the gas production per unit of COD is similar to that of root juice, the gas production per unit volume is less. This situation has arisen because the COD of the feedstock stem juice was less than that of root juice. The gas that is produced per unit of COD is comparable, suggesting that the biodegradable contents are similar. Both have been subjected to the juicing process and the lignin content appears to have been effectively removed. The COD removal efficiency was closer to 50% and, as mentioned above, may still have been rising.

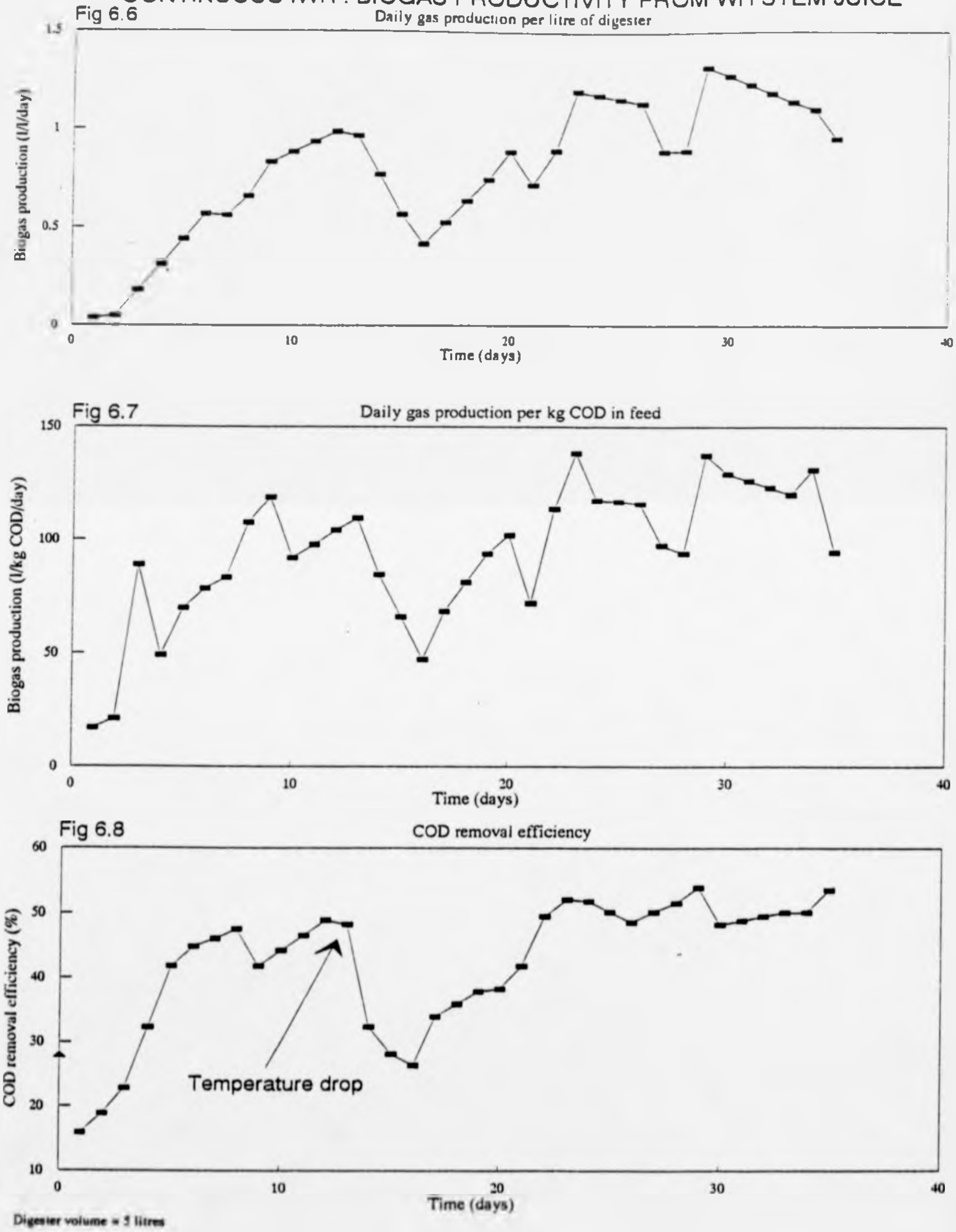
The batch trial results had shown a cumulative total of approximately 150 litres per kg COD and 1.25 litres per litre of digester volume over a twenty day period for stem juice sample number 1. The daily gas production, however, only reached a maximum of 21 litres per kg COD and 0.15 litres per litre of digester volume.

6.3.4 Leaf juice

Despite a much wider variation in the feedstock COD, in the region of 9,000 mg/l, the start-up of the leaf juice process appears to have followed a steadier development trend (Figures 6.9 to 6.11). The leaf juice was high in COD, compared to root and stem juice, with an average of approximately 25,000 mg/l. Maximum gas production was in the region of 130 litres per kg COD per day and 3.23 litres per litre of digester volume. The COD removal efficiency peaked at around 40% towards the end of the experimental run.

In the batch trials leaf juice sample number 1 had achieved a daily maximum of 0.4 litres per litre of digester volume and 21.5 litres per kg of COD. The cumulative gas production readings after thirty-five days were 207 litres per kg of COD and 3.7 litres per litre of digester volume, thus rather higher than the yield obtained with high-rate continuous digestion.

CONTINUOUS IWR : BIOGAS PRODUCTIVITY FROM WH STEM JUICE



CONTINUOUS IWR : BIOGAS PRODUCTIVITY FROM WH LEAF JUICE

Fig 6.12

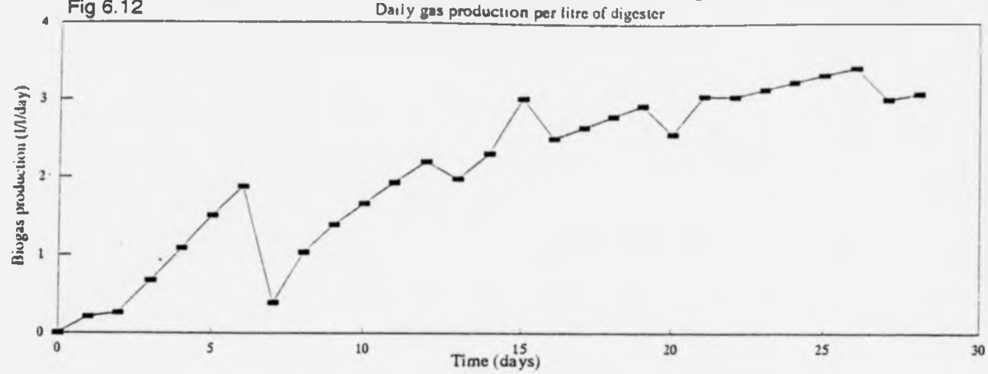


Fig 6.13

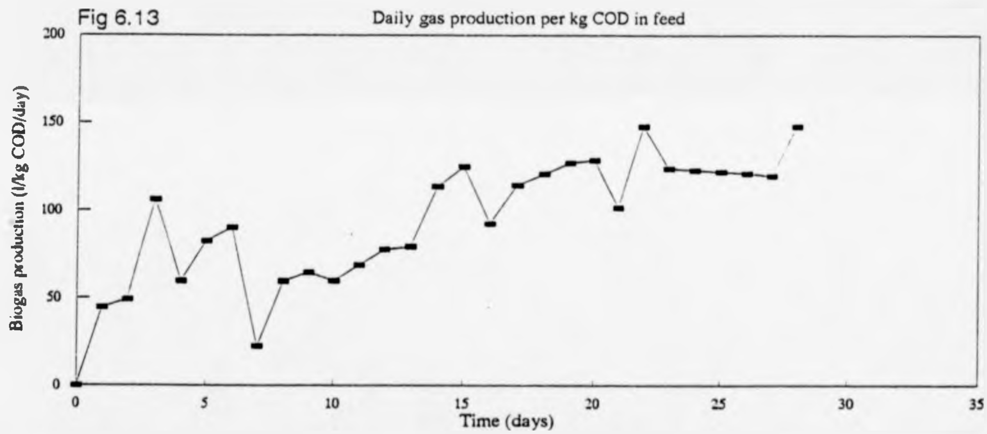
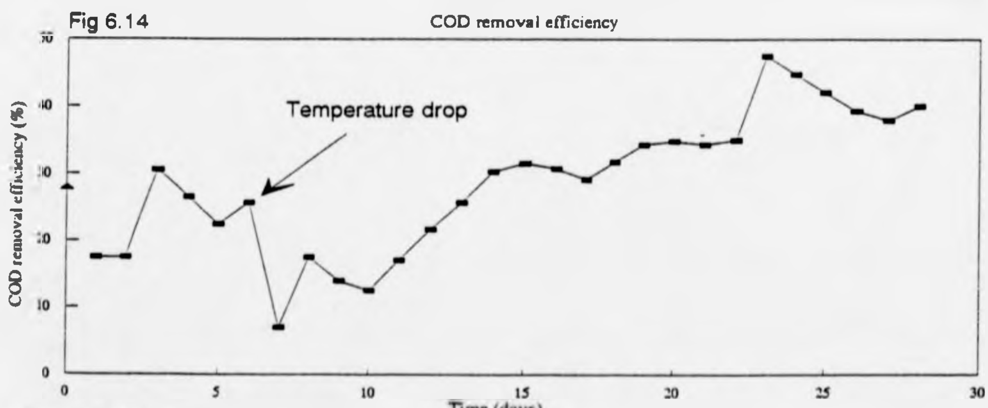


Fig 6.14



Digester volume = 5 litres

6.3.5 Whole plant juice

Whole plant juice performed as well as the individual components of the plant. As with the trials on batch digesters, this is probably one of the most important results from the current research. (Figures 6.12 to 6.14) There appears to be no advantage to be gained, in terms of gas production, from separating out the components in order to facilitate more effective anaerobic digestion.

The feedstock COD was in the region of 12,500 mg/l for the majority of the trial run. COD removal efficiency rose fairly rapidly to just below 50% and then was knocked back by the cold spell that was experienced in Bangkok. Following on from this it once again recovered strongly and appeared to peak out at approximately 50%.

Only one whole plant juice sample was run in a batch reactor, and this for only ten days. During this period the maximum daily production figures achieved were 13.53 litres per kg COD and 0.17 litres per litre of digester volume. This compares with daily gas production figures for the IWR of approximately 175 litres per kg COD and 2.0 litres per litre of digester volume.

6.4 SUMMARY

There are several aspects of the experimentation which are worthy of note. These are discussed below.

6.4.1 Ambient temperature operation

As can be seen from the results tabulated in Appendix 2, the ambient temperature remained at approximately 30°C $\pm$ 2°C for the majority of the experimental period. There was, however, one notable exception in the middle of December when the ambient temperature dropped to approximately 15°C during the course of one evening and remained barely above 20°C during the day. The effect of this drop in temperature is clearly visible on all the reactors that were running at that time. The gas production is seen to drop off and the reduction in COD removal efficiency, following on from the drop in temperature, is pronounced. Given the small volume of the IWR it is not surprising that the drop in ambient temperature should impact upon the bacterial colonies so dramatically.

The effect of ambient temperature on the IWR was more evident than with the batch reactors operating at this time because the batch reactors were not disturbed as much as the IWR's. Each day the water volume in each IWR was replaced with fresh material. The manner of

CONTINUOUS IWR : BIOGAS PRODUCTIVITY FROM WHOLE WH JUICE

Fig 6.15 Daily gas production per litre of digester

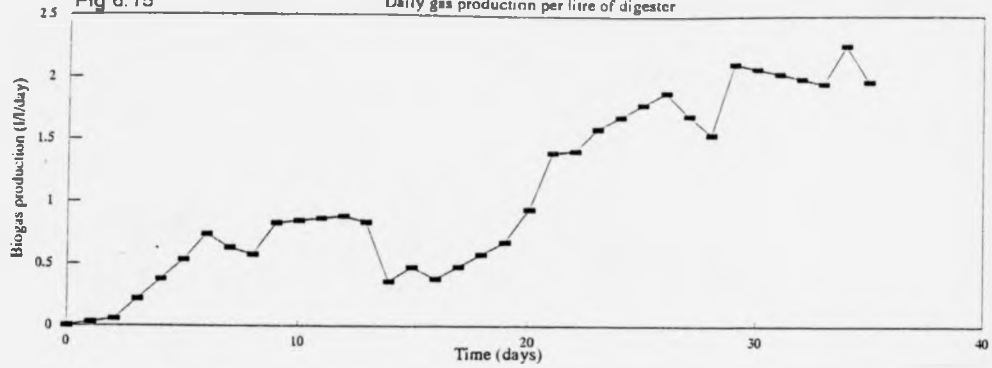


Fig 6.16 Daily gas production per kg COD in feed

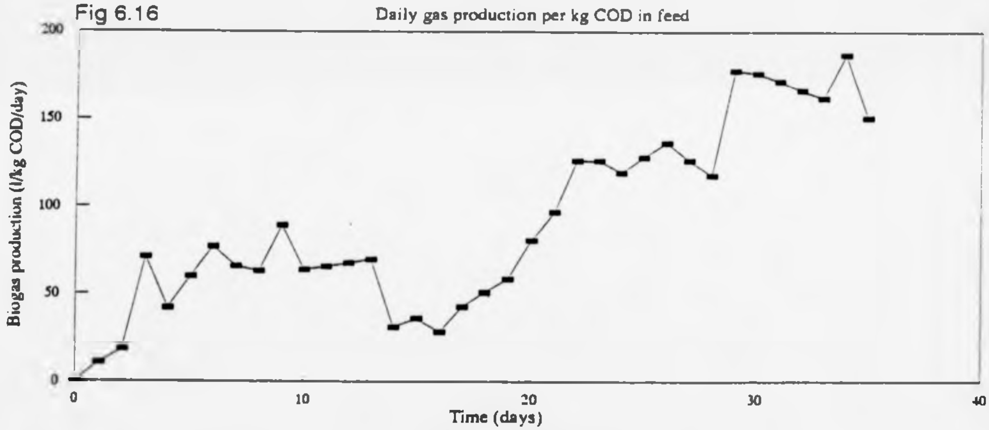
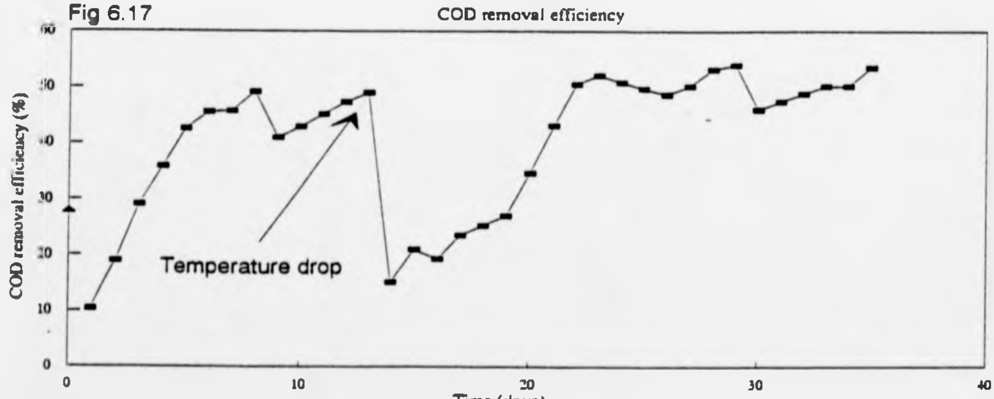


Fig 6.17 COD removal efficiency



Digester volume = 5 litres

preparation will have reduced the feed liquid to the ambient temperature. Ambient temperature operation will have a pronounced effect on the performance of commercial IWR's and it may be that some form of heat exchange may be advisable between the influent and the effluent lines, together with backup temperature control measures.

6.4.2 Retention time

The COD removal efficiency of the reactors tested was around about 50%. As a general conclusion, it may be considered that if the unit had a longer retention time the removal efficiency would be increased. Another manner of improving the removal efficiency, and hence the gas production, may be to increase the number of weir plates in the reactor. By increasing the velocity in each compartment the degree of mixing will be increased and hence the opportunity for contact between bacteria and substrate will increase. It may also be that the weir plates should be diverged only to a point at which the problem of blocking is mitigated and then, by using parallel walls, the velocity kept constant over the remainder of the riser section.

6.4.3 Overall operation of the IWR

The results of the experimentation presented above demonstrate that water hyacinth juice can be effectively digested in a continuous, multi-stage, up-flow anaerobic digester without encountering significant problems with blocking. The results also indicate that with the configuration used approximately 50% of the influent COD will pass through the reactor without being digested. This is a significant quantity to loose. The subsequent chapter, which addresses the commercial issues associated with operating the IWR will provide a clearer indication of the loss in benefit that results from this factor. There is no doubt, however, that the overall performance efficiency must be increased by further development work on the design selected.

Chapter 7

ECONOMIC AND TECHNICAL ASSESSMENT

Having discussed the various components required to construct the system proposed in the previous chapters of this thesis, and being in a position to draw upon practical work to assess bottlenecks, the following chapter will analyse the system application. This will include the use of the system model discussed in Chapter 4. The viability of water hyacinth utilisation will be addressed in the final section of this chapter.

7.1 DEFINITIONS

The scope for utilisation of water hyacinth begins with the individual cultivator and ends with large-scale utilities. To facilitate a meaningful discussion in this regard, it is useful to define scales of application, choosing throughputs that represent typical 'small', 'medium' and 'large' scale systems.

7.1.1 Scales of application

Biogas technology is more commonly associated with domestic schemes operating on the basis of a single farmstead household. The current work will consider the use of water hyacinth to produce biogas in such domestic applications, as well as larger, commercialised schemes where 21normal business evaluation will be applied. In describing such variations in the size of a scheme, the use of the words small and large-scale are clearly relative. Whilst the 22,000,000 m^3 anaerobic digester envisaged by Lecuyer (1976) would fall into the large-scale category, reactors of considerably less than this volume would still be considered as large-scale. The reason it is necessary to define scales of application more precisely than general terminology will allow is because the application of the various techniques discussed within the system under investigation will require differing levels of technological application. In a domestic situation, for example, it would not be reasonable to allow for a system which included a vacuum, ribbon-band, sludge filter for dewatering slurried plant. On the other hand, the feedstock requirements of a 12,000,000 m^3 reactor will not be satisfied with the harvesting efforts of human beings. Some form of mechanised harvesting at the large-scale level is an essential requirement. The reflection of economies of scale in an overall system assessment will be facilitated by defining the scale of application in a precise manner. Three scales will be considered, covering the full range of potential usage.

A small-scale system

A small-scale use of water hyacinth for the creation of energy and other sources of income will be based around an essentially domestic situation, with one individual manually harvesting water hyacinth and pre-processing it for introduction into an high-rate anaerobic digester. It will be necessary for this individual to devote a regular part of every day to the harvesting and pre-treatment requirements of the reactor. Work in Sudan has suggested that, where motivated, an individual may harvest up to one tonne of water hyacinth per day. This is considerably more than was harvested during experimental work in both Bangladesh and Thailand as part of the current research effort. In Bangladesh two individuals were employed for a part of every day and achieved a harvest of only approximately 50 kg of final product. Including the roots and leaves, which were separated out in the case of the Bangladeshi production system, this would equal a total harvest of approximately 100 kg wet weight, or 5 to 6 kg dry weight. A considerable amount of attention was devoted to separating the roots and leaves from the stem and preparing the stem for introduction into a chopping machine. With 100 kg wet weight it is possible to produce about 2.5 m^3 per day of biogas. This is equivalent to 0.6 kW (LCV) on a continuous basis. Using a high-rate digester, however, it is probable that this figure will be somewhat reduced.

It is the ability to harvest water hyacinth that defines the size of the small-scale application. It is reasonable to assume that a single household will require approximately $3m^3$ of biogas per day for cooking and lighting. This is equivalent to 120 wet kg of water hyacinth harvested per day and, taking Bangladesh and Thailand as the countries of interest, this quantity of water hyacinth would be readily harvested over a year from an area of water of approximately 150 square metres. The "small-scale" definition will, therefore, be based upon a harvest of 120 kg per day.

A medium-scale system

In the medium-scale utilisation of water hyacinth, the typical application will be on a community basis or as a small commercial business. For a small commercial business to successfully operate in either of the two countries of interest, it will be necessary to have a minimum income generation to cover overheads, wages and profit. In terms of current economics, with gas typically valued at 1 pence to 2 pence per kW hr and electricity at 4 pence to 5 pence per kW hr, the available revenue is the key factor which defines the medium-scale application. Starting with a building block of 100 m^3 of biogas per day, this would provide an income stream of approximately £8.00 for the gas on a daily basis. In Bangladesh a typical daily wage is around £1.00

per day, whereas in Thailand it may be double. For a small business to operate effectively it is necessary to have a reasonable margin. For this to be adequately satisfied there should be an income stream of a minimum of £50.00 per day. Coupled with an increase in wage costs there will also be a capital-cost requirement to be adequately covered. To achieve this by means of gas sales alone, the gas flow rate must be approximately 5,000 kW hrs per day, equivalent to a biogas flow rate of approximately 1,000 m^3 per day, requiring a daily harvest of 40 tonnes of wet weight water hyacinth. In order to obtain this harvest, an area of water approximately 4 hectares will be required. This will form the basis of the "medium-scale" definition.

A large-scale system

Moving into the large-scale or utility application, there is no practical limit to the scope of such schemes. The system envisaged by Lecuyer involved the generation of 2 gigawatts of electricity and may be considered to be a realistic maximum given the requirements of a social situation. However, to operate with a definition which is meaningful in the context of Bangladesh and Thailand, it is proposed that a small-scale power station capable of generating a continuous 7.5 megawatts of electricity be taken as the threshold of a large-scale application. To achieve this output it will be necessary to have a daily biogas flow rate of approximately 100,000 m^3 which will be achieved from 4,000 wet weight tonnes of whole plant requiring 4.5 km^2 of water area.

It is recognised that for each of the scales defined the challenge to organisation and administration will be significant. It is, however, a fact of commercial life that where the challenge is not significant the probability is that the business is either a temporary phenomenon or is unlikely to be of any significance. At each stage in the process, from obtaining the water area through harvesting, pre-treating and dealing with the products from the process, the small, medium and large-scale uses of water hyacinth will require professional and dedicated involvement.

7.1.2 Economic model

In Chapter 4 a basis for an analysis of the economic viability was set in place. There are a number of options for the individual unit processes. For example, the harvesting stage may be carried out manually, by channelling flow to a central point for collection at a weir, or mechanically. Each major alternative requires costing for insertion in the model.

Given the high number of options available, the system economics have been analysed via a spreadsheet. By varying the basic costings at any particular stage in the process it is possible to see their effect upon the overall system.

It is necessary to have chosen output measures so that the overall economics of the system may be assessed. Output measures include those for electricity and gas, fibre and fertiliser. Other parameters as identified on the spreadsheet may be varied to suit particular circumstances. For example, where electricity generation is considered, availability of 90% has been chosen. In the case of larger units it is possible that availability should be in the region of 95-97%. This will have a significant impact upon the economics of large-scale operation and the facility to adjust this availability figure is embedded into the spreadsheet. A further set of relationships, namely those relating fibre and fertiliser output to (wet weight) water hyacinth input may be varied dependent upon the particular system envisaged. If it is, for example, intended to encourage growth of plants with short stems, the quantities of fibre produced per kilogramme of wet water hyacinth will be reduced.

A range of intermediary values have been included in the spreadsheet. Thus each 'typical' system (small, medium, large) defined above has been treated as the centre of a band, or "median". The other systems in each band have been costed by means of scale factors applied to the costs for the median system in that band. Arriving at these scale-up factors for small, medium and large-scale bands provides a basis for evaluating realistic commercial parameters.

The cost of each stage in the process has been split into labour, capital and power costs. In the case of conversion into electricity, an operation and maintenance cost has also been included because the operation and maintenance of electricity generation plant is a significant increase in complexity compared to the other stages of the operation.

Labour rates may be varied within the spreadsheet so that their immediate impact upon system viability can be observed. The spreadsheet has been set up in pounds sterling, but may be readily altered to other currencies. Alternatively, it is possible to introduce conversion factors at any particular stage. For example, if all the inputs were converted to Taka, the system economics would automatically convert to Taka. The Taka is the currency of Bangladesh.

The range of scales examined was deliberately made very wide, from 3 m^3/day to 1,000,000 m^3/day of gas production. To date, the majority of biogas schemes using harvested biomass have been in a small-scale band. Medium and large-scale applications using water hyacinth have received considerable attention, but none have reached commercial viability.

7.2 DISCUSSION OF MODEL PARAMETERS

In the application of a process for utilising water hyacinth, there will be a great many factors coming to bear. Indeed, it is surmised that the key reasons for biomass utilisation not achieving significant realistic levels of application concern non-technical factors. The following section addresses some of these.

7.2.1 Growth seasons

The length of the water hyacinth growing season is a primary factor in determining the viability of utilisation schemes. In certain parts of the world, the growing season may be as short as six to seven months. In other locations, such as Bangladesh or Thailand, there is growth throughout the year, albeit at varying rates. Sizing a utilisation scheme upon a given area of water, requires a thorough understanding of the dynamics of growth in that location. Maximum growth rates with a doubling time of six days, must not be assumed for the purposes of system sizing. Whilst such growth rates may persist for a number of months, it is probable that the baseline growth rate will be significantly less.

Small-scale

In the case of small-scale applications, where a growth area of 100-200 m^2 is envisaged, there is often scope for significant buffering. By increasing the growing area by 50%, the maximum and minimum growth rates will have less impact upon the plant operation than will be the case for larger schemes. Fluctuations in growth rates may, therefore, be allowed for by making a moderate increase in the size of the growing area.

Medium-scale

In the case of the medium-scale, where a growing area of four hectares is typically required, there will be less scope for buffering. Such an area is unlikely to be waste land and will probably be subject to formal rental arrangements. Should it be envisaged, for example, that in one particular location it would be desirable to have 50% additional growing area so as to accommodate a reduced growth rate, this would imply an additional two hectares. Given the modest income likely from a medium-scale system, an additional two hectares may be unacceptable. It is, therefore, necessary to size medium-scale operations more carefully than small-scale ones. It is envisaged that in medium-scale applications, the various unit processes involved in the system will have a turn-down ratio capable of accommodating variations in growth rate. The use of a turn-down ratio in countries in South East Asia, would ensure that medium-scale systems could operate throughout the year.

Large-scale

In the case of large-scale systems, the problem of growing areas becomes most severe. There is some argument to suggest that the system should be sized to accept the minimum growth rate so that operation of the plant can be guaranteed for a maximum period of time. However, the rental of the growing area is likely to be small compared to the capital cost of the plant and equipment involved, plus the associated overheads involved in running such a large system. With the sums of money that may be generated, the use of five square kilometres will not be excessive. In Bangladesh, where a large percentage of the area of the country is permanently covered with water, water space has a very low value. In Thailand, the situation is not comparable. There are not a large number of such water spaces available and the cost of the water area is likely to be greater, as it will probably need to be manmade. The use of existing man-made water spaces such as those created to feed water to hydroelectric schemes or irrigation systems may be considered. Set against this approach is the problem of evapotranspiration. The increase in evapotranspiration, due to the presence of water hyacinth, may have a significant impact upon hydroelectric or irrigation systems.

A clear understanding of growth rate patterns in specific localities will be of prime importance in sizing any particular scheme. Each particular location will have its own opportunities and difficulties for each potential scale of application.

7.2.2 Distance from site of production of feedstock to point of utilisation

One of the great disadvantages of using water hyacinth is the low ratio of dry matter to wet harvested plant. Where extended distances are involved in transporting harvested plant to the point of use, substantial costs are incurred in transporting water which will not contribute to the system viability in any sense at all. It is, therefore, essential that in all scales of application transport distances from the growth area to the utilisation plant are the minimum that can be practicably obtained.

Small-scale

In the case of small-scale systems it is envisaged that the harvesting will be carried out manually and that labour costs are low. In this context transportation over distances up to 1 km (0.1 tonne-km in the median system) are tolerable but transport over several kilometres would not. The growing area itself will not exceed 100 metres.

Medium-scale

It is envisaged that from the medium-scale system upwards, it will be necessary to mechanically harvest water hyacinth, or to employ some form of automation to the harvesting process. With a 40 tonnes per day requirement, it would be possible to manually harvest employing 40 harvesters each required to collect 1 tonne per day, but this would have a significant cost, even in Bangladesh where labour is inexpensive, and would take some skill in management if it were to be utilised efficiently. It was noted by Philipp (1983) in the Sudan that unsupervised labour was approximately one third as effective in this task as was supervised labour.

This being the case there is significant advantage to be gained by ensuring that the harvesting process always results in feedstock being as close as possible to the point of utilisation. This will in all probability be achieved most simply by ensuring that the natural flow of water through the system carries the plant to the point of harvesting. To obtain a harvest of 41 tonnes per day approximately 0.25 hectare will need to be harvested on each particular day. This is an area 50m x 50m. It is quite conceivable that a movement of 50 m per day may be achieved by natural water flows, and that, therefore, the distance involved in transferring harvested product to the point of utilisation will be minimal.

Large-scale

In the case of large-scale systems it will be necessary to harvest about 4,000 tonnes/day. This is equivalent to a surface area of 26 hectare, or approximately 500 m x 500 m. Once again it is quite feasible that water flows may be arranged to facilitate a 500 m movement per day. In the particular case of large-scale systems it is likely that harvesting will be a twenty-four hours per day operation and in order to ensure that minimal distances are involved a flow rate of 20 m/hour would be required. Once again, this is not inconceivable and there would be great advantage to be obtained from ensuring that the point of harvesting was always adjacent to the point of use.

It is reasonable to assume, therefore, that by various means the transport requirement from the growth area to the utilisation equipment will in all cases be sufficiently small to incur a minimum penalty. Where this is not the case great care should be taken in assessing the implications for overall system viability.

7.2.3 Product transport

In the case of product transport there are numerous variations which would need to be considered. The transport of liquid fertiliser, which will be the product from the wet anaerobic process, to where it can be applied, may be prohibitively expensive. In the case of a large-scale system the quantity of fertiliser may exceed ten thousand tonnes per year. This could feed many square kilometres of farm land and hence require transport over up to 20 kilometres. Being substantially comprised of water it has a low value per kilogramme. The value attributed to the fertiliser must be offset against the cost of transport. In the case of fibre, however, value per unit weight is much higher. Fibre is traded internationally and the cost of transporting it large distances is tolerable.

With both gas and electricity, it is likely that any system set up the for the sale of either of these commodities will be designed around a specific point of sale. It will not, for example, be economic to transport gas over great distances unless the flows are high and the consequent cost per unit transported is small. Similar arguments will apply for the use of electricity. In the case of electricity, however, it is not uncommon to find, in the vast majority of countries around the world, a distribution network which would facilitate the transfer of generated electricity to points of use. Generally, the utility of electricity will have added benefit over the utility of gas. In small-scale applications electricity, if generated, will be used essentially in-house, in large scale applications where extremely large electrical outputs may be obtained, and it will be essential to have a specific network for transferring such capacities to remote points of use.

In the scenarios considered within the model for Bangladesh and Thailand, the income derived from electrical and gas systems is roughly equal. In reality, it is probable that the market for electricity will be more sustainable than that for gas. Once again this is very much a matter specific to particular locations.

7.2.4 Feedstock Preparation

Small-scale

The method of feedstock preparation utilised in the current research programme in Thailand may only be taken as a model for usage in a small-scale utilisation scheme. It is quite conceivable that the mincing and pressing actions may be achieved effectively by manual means. One thing is quite certain; employing an electric motor, as was done in Thailand, will result in a disproportionately large energy bill: a process with a higher productivity (kg juice per kW hr of shaft energy) is essential. Several simple adaptations can be made which would speed up the whole process and introduce the possibility of manual juice preparation. Prior to feeding the water hyacinth into the mincer, it would be useful to chop the plant into sections of 2-3 cm long, this can be accomplished by a mechanical chopper of the kind employed in Bangladesh, operated by hand. The chopped feed may then be passed into a hopper which allows a steady concentrated flow of feedstock into the mincing machine. This again would ensure that the process operated at a maximum efficiency. In Thailand the method employed involved hand feeding chopped portions into the throat of the mincer which resulted in a considerable amount of unutilized chopping and auguring action. Finally, with some careful thought, it is probable that a roller could be arranged which would carry out the necessary pressing action. The rollers that were actually readily available on the market were not quite right for the intended duty. A certain amount of elasticity in the roller surface, such as is found on wringing machines for drying out clothes, would help considerably. The problem with rigid rollers was that the variability in the thickness of feed caused the roller to be either ineffectual or to jam. Rubber or sprung rollers would alleviate this problem.

Medium-scale

When it comes to feedstock preparation for the medium-scale system envisaged, it will be necessary for the feedstock preparation to be fully mechanised. It is not conceivable that 41 tonnes a day of raw water hyacinth can be processed manually. This being the case, the method of feedstock preparation will need to be evaluated further. The mincing action involved with the plant employed in Thailand would push power requirements to an unacceptable level. Crushing is in actual fact a common requirement in the process industries, and there are numerous options available for large-scale applications. The possibility of using biogas fired engines to directly drive any feedstock preparation plant that may be required is one that should be given serious consideration. By directly converting biogas to mechanically shaft power, the losses involved in converting shaft power to electricity and then electricity back into shaft power may be avoided. The medium-scale use reflects the level of application where mechanisation becomes necessary and yet affordable.

Large-scale

With 4,000 tonnes/day of raw weight water hyacinth requiring to be processed for delivery to an anaerobic digester, it will be necessary to employ equipment that would not be justifiable in either the small or medium-scale applications. The equipment will probably be specifically designed for the particular application.

The question of the economics of feedstock preparation is one which will require further investigation. It has not been the intention of the current work to address this problem in any depth. The brief discussion and evaluation of the energy required within the scope of the Thai experimentation has indicated that care must be exercised in the choice of equipment for both pulping and extracting the juice from water hyacinth. There are two critical productivity measures that must be assessed. The first is the output in kilogrammes per unit (eg MJ) of work required. The second is the fraction of COD transferred from raw water hyacinth into juice. It may well be that in the medium to large-scale applications, feedstock treatment entailing aerobic decomposition or dilute alkali pre-treatment may be justified. Work in Bangladesh has indicated that a certain degree of aerobic pre-treatment is helpful and should not significantly reduce the volumes of gas produced. The optimum duration of such aerobic pre-treatment will need to be researched.

7.2.5 Water hyacinth properties versus methods of preparation

Small-scale

There are a number of physical characteristics of water hyacinth which may be used to enhance performance of a system, both in the pre-treatment of the plant and in the method of operation of the reactor. It has commonly been suggested, for example, that the root portion should be discarded prior to anaerobic digestion. The current round of experimentation has demonstrated that where treated in a manner that breaks down the root, it will contribute to the production of gas in a useful manner. The fact that the root often comprises up to 40% of the wet weight of the plant means that efforts expended in removing it may be extremely wasteful. A further factor which will require attention is the fibrous nature of the stem portion of the plant. It is essential, where the pulping is carried out by means of a mincing action, that the stem is chopped and reduced in size. This is particularly the case where small-scale equipment is involved because the clearances in the digester passages are necessarily smaller.

Medium and large-scales

The volume of throughput required in the medium to large-scale applications will necessitate the use of pulping and de-watering plant that will not be affected by the relative size of the water hyacinth portions. In small-scale situations,for example, it is necessary to chop the root so that it will enter the throat of the mincer, but in large-scale apparatus it is probable that the whole plant can be entered into the pulping equipment without any form of preparation. The removal of unnecessary stages in the process of pre-treatment will result in cost savings and an improvement in the economics of the whole system.

7.2.6 Reactor problems

During the course of the trial runs carried out in Thailand, it was observed that occasional blocking of the vertical risers occurred. Despite having the feedstock juiced, there remained a significant suspended solids fraction which coagulated and led to channelling and eventually blocking. To resolve this problem in the experimentation, probes were inserted through the digester lid and the blockages removed. This practice would, however, pose significant problems on operational plant.

Small-scale

A small-scale reactor will have a volume between 50-100 litres. Being comparatively compact it is quite feasible that this reactor can be arranged in such a way that a daily service ensures that any blocks that may be forming are removed. This may be achieved simply by probing each riser section from the lid as was done during the course of the experimentation in Thailand. A further option may be to draw liquid from the base of each riser section and return it in through the top.

Medium-scale

In the case of medium-scale applications, the volume of the digester will be to the order of 20 m^3. With a reactor of this volume it will be essential to have a method for purging any blocks that may form in the reactor, probably by re-routing, flushing or purging rather than locating individual blocks and preventing their further development.

Large-scale

In the large-scale applications envisaged, it will be possible to install equipment that will measure both flow rates and densities in the various riser sections. By this means it will be possible to identify locations where channelling may be occurring and with methods similar to those of the other scales, such as purging and flushing, it will be possible to selectively control the tendency towards blocking.

The problem with blocking is one that has not been fully addressed within the current experimental work. At the commencement of the research project, it was anticipated that the juicing process would itself result in a liquid that would not be conducive to blocking. There has, in fact, been a substantial and dramatic improvement in the operation of the multi-stage upflow reactor. There remains concern that this matter should be isolated and addressed as a separate problem requiring resolution, especially where medium to large-scale utilisation is envisaged.

7.2.7 Costs of equipment

Small-scale

It is in small-scale applications that the cost of equipment will be most difficult to assess. A straight commercial decision, as presented in the modelled evaluation in section 7.4.1 below, proves the small-scale to be barely viable. Labour costs, which can dominate at this level of activity, need to be carefully evaluated, almost on a case by case basis.

For the successful operation of small-scale schemes it will be necessary to use low cost equipment. The prime capital expenditure will be for the pre-treatment equipment and the anaerobic digester. By using commonly employed, locally available machines it is likely that juicing costs can be kept to within acceptable limits. A low cost digester will need to be designed and costed using locally available material and labour rates.

Medium-scale

Serious investment in plant commences in this range of application. To some extent the choices are less complex as the input cost and the output values are more clearly defined. Equipment used will be of a more industrial variety. There will, however, remain some scope for local craftsmen to fabricate lower cost equipment.

Large-scale

In large-scale systems the use of complex plant and equipment will be required. It is likely that they will also require a great deal of instrumentation in order to minimise down-time. The revenue streams that can be generated are large enough to allow the selection of reliable equipment that has been industrially manufactured and supplied with guarantees.

7.2.8 Labour time and costs

Small-scale

When reviewing the question of labour time and costs in a small-scale scenario one of the prime elements to note is that the operation is essentially non-commercial. Whilst it is possible to include a cost for labour time, (and where labour is expended in a water hyacinth utilisation scheme, as opposed to earning income, this may be a realistic method of assessment) it is often the case that personal time is not valued at the same level as time spent working for others. Where the task is to harvest 120 kg per day and process this into an anaerobic digester, it is quite feasible that non-earning labour may be employed, in which case the element of the labour time would be costed into the scheme at a very low rate. Labour time costs and capital investment in basic machinery will need to be of a very low order. Any expenditure in plant will have to be thoroughly justified.

Medium-scale

In this situation there are clearly drawn commercial lines between the option of investment in plant and equipment or carrying out operations manually. Commercial investment criteria vary from country to country, and it may be that in one location a two year pay back would be considered adequate, whereas in another a five, six or even seven year pay back may be considered acceptable. In Bangladesh, for example, given the historic political instability and the proclivity of the country as a whole to disasters, there is a general reluctance to consider time horizons of more than a few years, at most. It is, therefore, to be expected that manual labour will be employed to a far greater extent in Bangladesh than in Thailand. Thai labour is more skilled and labour costs are higher per person employed but are likely to comprise a lower percentage of the overall operating cost structure.

Large-scale

With large-scale uses of water hyacinth there will be no alternative but to mechanise as much as possible of the whole process. This is necessary simply as a matter of achieving the throughput required. With 4,000 tonnes per day to be harvested and processed into an anaerobic digester, it will be impossible to manage any significant percentage of this with manual labour. The choice of equipment may still revolve around a relatively large manual labour input, but should excessive numbers be involved it is likely that the whole operation will be prone to enormous overheads.

7.2.9 Overall product creation versus input

There are a number of elements to the proposed scheme that would fall under this heading. The first is the question of engineering the feedstock to maximise the output. Where fibre is a highly prized product, it would be advantageous to encourage the growth of long stems. Where fertiliser is viewed as a key product, there will be advantages in seeking nutrient input from either sewage works or other suitable trade effluent sources. Where gaseous product, in the form of methane or carbon dioxide, is valued over and above that of fibre or fertiliser, it may be that the retention time will be slightly increased to maximise gas, at the expense of other product creation. Increasing retention time will slow the bulk throughput and will reduce the amount of fibre that is produced on a rate basis.

- *Small-scale*

In the small-scale situation the question of relative product output will be of less significance than in larger scales. The general products of interest in the small-scale application will be gas and fertiliser, in that order of priority. Small-scale input selectivity may in fact occur with individuals deciding to put in, for example, more leaf and less stem, but such decisions will be of an individual nature. The possibility of encouraging the small-scale production of paper and board pulp from water hyacinth stems has been considered in Bangladesh and it may be that such applications can be combined with anaerobic digestion for the production of gas and fertilisers.

Medium-scale

It is in the medium-scale that the balance between input and output becomes critical. The economics of each particular situation will be more finally balanced than will be the case for larger scale applications, and the need to maximise particular outputs to suit local market conditions will be a more pronounced commercial requirement. With a four hectare growing area it will also be realistic to consider the optimum mechanism for growth. With a daily raw weight harvest of approximately 40 tonnes there could be significant quantity variations in both fibre and fertiliser, contingent upon the methods in which the plant is actually grown.

Large-scale

In the case of large-scale systems, it is to be expected that commercial viability will be built primarily upon energy in one form or another as the key product. With the quantities involved of other products, it is likely that there will be variations of both seasonal and market importance in the income stream. With the level of financial investment required in large-scale operations, considerably more analytical input to the assessment of markets will be required than for small and medium scale operations.

7.2.10 Equipment operation

Operational practices in the implementation of water hyacinth utilisation will vary enormously depending upon the scale of the system involved. The levels of worker discipline and the sophistication of the various checks and controls used to optimise system performance will be proportional to the revenue streams that are anticipated. The small-scale scenario will essentially be an amateur operation in which certain basic skills will be developed and applied as operational experience is gained. Medium-scale equipment operation will fall into the small business category where supervision will be at a level which ensures satisfactory performance from a workforce of largely unskilled workers. In large-scale operations the workforce will largely be of a professional and trained nature. Skilled technicians will be required to operate and maintain process plant and equipment, with a significantly lower input from semi-skilled and unskilled labour.

7.2.11 Design improvements

The process of moving from experimental work into commercial activities will involve a wide range of technical improvements to any system proposed on a theoretical basis. The current round of experimentation has highlighted the principle areas which would benefit from attention, as well as having made in-roads into some principle obstacles. The major difficulty associated with retention times and digester volume has been the primary concern of this thesis. A wide array of lesser difficulties that would properly fall under the heading of design, as opposed to research, have also been highlighted. These must, however, be assessed in some detail to ensure that they do not contain ingredients which may lead to more complex problems

Harvesting

The problem of harvesting becomes significant once the medium-scale scenario is considered. It will be essential that harvesting techniques are developed which facilitate the minimum of labour time and energy input. Work in the United States has demonstrated that a roaming mechanical harvester can be extremely efficient in terms of raw weight harvested per unit of time. The energy cost of such a harvester, however, is another matter.

One of the principle barriers that will be encountered in the utilisation of biomass, in the manner envisaged, is that of system output versus system parasitic energy requirements. From the information and data available, it would appear that the only realistic option for harvesting, is to ensure that water hyacinth growth uses the natural flow of water to carry the plant to the point of harvesting. Once at this location the optimum would be for the plant to fall into a mechanical pre-treatment system, rather than requiring to be lifted, transported and then entered into mechanical pre-treatment. Such harvesting may be facilitated by the use of wears and separation grids.

Pre-treatment

Within the system currently envisaged, pre-treatment is likely to be the most energy intensive unit-process involved. Assessing data obtained during experimentation in both Bangladesh and Thailand, if care is not taken in selecting this equipment, the whole of the energy output will be required to operate a mechanical crush and press. This is a key area, and further development work is required to isolate the factors involved.

Anaerobic digestion

The principles involved in the multi-stage upflow anaerobic digester would appear to fit with the strategy of separating fibre from soluble organics. There does remain, however, the possibility of blocking. Design work will be necessary to ensure that systems operate in a manner which can effectively deal with digester blocking. Other aspects of digester design, such as controlling heat loss with variations in ambient temperature, including the possibility of solar heating, as well as making sure the means of gas take off is satisfactory, will fall under the heading of technical design. Many methods are available and it is simply a question of methodically analysing the options to arrive at the optimum solution to the design problem. The remainder of the system processes, ie. storage, distribution and conversion of gas to electricity are well developed disciplines and will require the application of expertise as opposed to the input of original design work.

7.2.12 Social factors

Social factors will play a greater role in small-scale applications and a far less significant role in large-scale applications. The mechanisms for controlling large industry are, in general, well established throughout the world. Whether these mechanisms are adequate, or indeed ethical, is a matter of local politics. In Bangladesh, for example, it is possible to build chemical works in the centre of urban populations. In Thailand, there are situations which may be considered to be of a similar nature. Where large sums of money are involved, it is usual that social factors, which may turn into obstacles, will be of less consequence, unless there is some significant social impact in the form of environmental damage.

In the case of small-scale schemes, one of the key difficulties will be the question of ownership. Where no value is attributed to water hyacinth it may in general be collected and used, perhaps as an ad-hoc fodder for ruminants, without any conflict occurring between the parties involved. As soon as water hyacinth appears to have a value, however, it is probable that the question of ownership will be dealt with in a less relaxed manner. It is to be expected that this will be a major obstacle to small-scale applications and the question of water area ownership should be clearly established before any attempt is made to operate such systems. The problem of ownership may become most acute with medium-scale applications if the necessary water areas are to be obtained from essentially communal sources. The concept of water hyacinth being a social nuisance that should be disposed of by any mechanism, to the universal satisfaction of all members of society, will be one that will be confounded at the personal level. In generally poor societies, where benefit is observed to be gained from a valueless substance or product, it is to be expected that value will be attributed. It may well be that certain schemes will be based on the purchase of harvested water hyacinth from local inhabitants. It should be noted, however, that as soon as the value of water hyacinth passes anything but a nominal figure, the economics of the whole scheme immediately falls into jeopardy.

7.2.13 Return on investment (ROI)

Criteria for viable returns on investment vary from country to country and from institution to institution with any one particular country. For example, a venture capital operation in the United Kingdom, in the current economic climate, would not be interested in any investment which provided less than a high-thirties percentile return on an annual basis. Other institutions, such as the recently privatised water and electricity companies are prepared to consider returns in the region of 20% per annum. It is unlikely that returns much below this figure will be acceptable in any country or economic situation. This stringent commercial view will have greatest impact on large-scale operations where large sums of money will be involved, both in terms of capital investment and anticipated revenue streams. It is feasible that medium-scale schemes will operate more on the basis of communal benefit with less emphasis on strict financial return. There remains a possibility that medium to small-scale applications may be engineered to provide a minimum of capital investment whilst retaining a reasonable product output. The small-scale scenario will not be evaluated on the basis of ROI other than at a purely subjective level. Individuals will view the benefits against the investment and time requirement and come to decisions about the value of the opportunity. Despite these varying views there is no doubt that should the fundamental system viability not exist the use of water hyacinth will remain the province of the enthusiast.

7.3 UNIT PROCESS OPTIONS

Having considered general matters that would apply to water hyacinth utilisation, the specific options that would apply around world will be delineated for use in the economic evaluation in the final sections of this chapter. From this base, it will be possible to formulate a more specific assessment of water hyacinth utilisation potential.

7.3.1 The range of options

Growth

Within the range of choices for growth there are two primary options. The first is cultivated growth, where specific areas of water are set aside and engineered to optimise growth and harvesting. The second is wild growth, where water hyacinth is collected from natural waterways. Viewed from the context of scale of application, the possibility of wild growth being used commercially will be fraught with uncertainty and risk. Despite the abundance of the plant in certain locations at certain times of the year, it will be essential that planned and managed harvesting can be accomplished. This will only be feasible where the water area is controlled effectively. Wild growth will, therefore, only be a serious option for small-scale applications.

Once it is decided that managed growth is necessary, the next set of choices will cover the manner on which the growth of the plant is organised. The possibility of increased harvests by additions of fertiliser, or recycling some of the effluent from the anaerobic digester must be considered. Where medium and large-scale schemes are established the maximisation of output from the growth area will be of great importance. The use of sewage-works effluent will be a serious contender for inclusion in such as scheme. There is clear evidence (eg. Dymond, 1948) that additions of nitrogen to a growth of water hyacinth will have a dramatic influence upon the rate of growth.

Harvesting

In a system which relies on the harvesting of wild water hyacinth, manual collection and transport to the point of utilisation would be the only realistic option. Whilst it is technically possible to mechanise the whole process, the cost of energy, governed by world energy prices, would immediately render such a scheme non-viable. In a cultivated-growth utilisation scheme, there have been a number of methods suggested in the literature for the removal of water hyacinth from growth ponds. Such techniques include overhead grabbers and water-edge conveyor systems. Water-edge conveyor systems would tend to be appropriate in situations where it is possible to engineer the flow of water hyacinth to a specific point within a growth pond. The concern must remain, however, that any system which relies on energy and significant capital expenditure will reduce the overall efficiency of the process, and it will be more effective to expend initial efforts in constructing a weir system to control the direction of water flow and provide a point of collection for water hyacinth.

Pre-processing

The use of a mincer and a manual press, as employed in the current IWR trials, will only be considered for small-scale applications and, taking the figures for electricity consumption achieved, would only be acceptable if a greater efficiency could be attained.

The end product in the pre-processing of water hyacinth is available from a variety of methods. The widely used, manual, sugarcane crusher for preparation of drinks in Bangladesh and Thailand may be amenable to adaptation for water hyacinth juicing without an excessive research and development effort. Such a system would probably work very well for small-scale applications, achieving both the slurrying and the pressing in one action.

Where larger quantities are required to be processed it is probable that greater attention will need to be paid to industrial processes. For example, a cushing pump is available on the market, called the "muncher" which will both extract and pulverise solids entrained in a liquid flow. Constructed with interlocking positive-displacement rotors such a unit would potentially be ideally suited to first-stage slurrying. Once slurried there are a number of methods of removing juice from solids. As an example, a vacuum filter is often used to pull off liquids from a sludge. Development in this direction will need to pay particular attention to the energy requirement of each stage set against the process efficiency, in terms of COD transfer from whole plant to juice.

Anaerobic digestion

Options available for use with the IWR include the possibility of insulating the unit and using a counter-current heat exchanger on the influent and effluent lines in order to maintain a steady process temperature. Another possibility will be to us solar heating to raise the temperature of the digester, thereby increasing process efficiency. All such additions will increase the complexity of the system, making it more prone to failure, and also raise the initial capital cost.

Storage

The problem of storage covers solid, liquid and gaseous outputs. Solids storage, in the form of fibre, will not present problems any different from those commonly encountered in arable farming. The volumes of liquid that need to be stored, for use as fertiliser, may be such that it very rapidly becomes a non-viable output. With a liquid store equal to one week's output the volume of the store will become close to that of conventional digesters and the advantages gained by reducing the digester volume will be lost. It may well be that in many instances the quantities of liquid that can be realistically considered as a viable commercial product will be only a percentage of the total output of the system. Where agricultural land is close by there will be a better chance to employ a larger portion of the output. Within a medium-scale system there will be around 20 cubic metres of water to be disposed of per day. In a large-scale system this figure will rise to approximately 2.000 cubic metres. The latter flow rate would form a good basis for an irrigation system.

7.3.2 Selection of options for Thailand and Bangladesh

The following section will identify the options to be considered for each scale of application for both Bangladesh and Thailand. This will lead into a consideration of the viability of the use of water hyacinth as a commercial resource. There are several aspects which may be considered to be very similar in the two countries. It is the differences that lead to a varied assessment of viability in the two locations.

Growth

In the case of Bangladesh and Thailand the opportunity for the manual harvesting of wild growing water hyacinth is of great significance. The water area in Bangladesh is a significant percentage of the total land area of the country. Apart from coastal areas, where the high salt content prevents the growth of water hyacinth, it is common to find water hyacinth growing abundantly in ditches and ponds and all types of stagnant and flowing water bodies. Such a situation would be ideally suited to the collection of wild water hyacinth for use in small to medium-scale applications. With regard to large-scale applications the area of water is of such significance that feedstock requirements would not be readily accommodated from uncontrolled growth in natural waterways. It is, therefore, proposed to assess wild growth for small to medium-scale applications and cultivated growth for medium and large-scale application

Harvesting

One immediately apparent factor in South-east Asia, which would separate it from, for example, Florida in the United States, is the cost of labour. In Bangladesh it is possible to employ unskilled labour for approximately one pound, or less, per day. In Thailand the rate for unskilled labour is approximately double this figure. No attempt here is made to argue the case for high or low wage rates other than to comment that the comparatively low wage rates for unskilled and semi-skilled labour in South-east Asia is one of the key building blocks for the rapid development of this region of the world and, much as it would be desirable to see high wage rates, this would not be a realistic objective within the framework of any commercial industrial project. For this reason, manual harvesting is an option which must be considered seriously. It will be the only option considered for the small-scale application. It will be a serious option for the medium-scale application, and, in all probability, it will not be feasible for large-scale application.

The options to be considered here will be the manual harvesting of wild plants and the manual harvesting of cultivated plants in both the small and medium-scale scenarios. The use of mechanical single-point harvesting will be investigated for medium-scale applications and the channelled flow of water, in cultivated growth situations, to a weir will be considered for large-scale situations.

Pre-treatment

Manual pre-treatment will be assessed for both Bangladesh and Thailand in the small-scale scenario. Only mechanised pre-treatment will be considered for medium and large-scale systems. In these latter there will be an operational cost associated with electricity consumption. This will be assumed to be a given percentage of the energy content of the feedstock.

Anaerobic digestion

All systems will be operated at ambient temperature without any attempt to buffer out dramatic variations in the local temperature conditions. The "cold" spell experienced in Bangkok during the current trials proved to be the exception that proved the rule. Such an occurrence in the region was an exception that took everybody by surprise. It is not commercially viable to build systems that can cater for every random event. In other parts of the world, where prevailing weather conditions involve regular temperature variations, it would be advisable to include levels of protection to system shock, commensurate with the probability of such variations.

Storage

A product storage factor is built into the spreadsheets employed as part of the economic modelling in order to assess the impact of this aspect upon overall system viability. With small scale systems the full product may be costed in as a utilised output. In medium and large scale systems this will need to be tempered by a percentage of use.

7.4 OPERATION OF THE ECONOMIC OPTIMISATION MODEL

The following section involves the setting up of classic scenarios for each of the scales of application being considered and an appraisal of the salient features.

7.4.1 Common features

There are a number of aspects that will be addressed in the economic models that do not vary. These are listed below with explanations, where necessary.

Total gas production available is taken as 420 litres per kilogramme dry weight. A function is included to allow for a reduction in the total gas production achieved in practice. This will have the effect of increasing the water area required, and the daily harvest, in order to achieve the specified flow rate of biogas.

The growing period and the rates of growth in Bangladesh and Thailand are taken as being identical. Adequate records do not exist to differentiate precisely how growth in these two countries may vary. With regard to weather conditions, growth is a function of temperature and humidity. These two parameters are comparable in Bangkok and Dhaka. Within the context of the accuracy required, the approximation of equal growth will satisfy current requirements.

Plant dry weight is taken as 6% of the wet weight.

Output values are also kept at the same levels for the two countries. In the case of gas and electricity, internal prices are largely governed by world energy prices and thus only minor variations will occur. The pricing mechanisms for the bulk purchase of electricity and gas does, in fact, vary significantly but the intention here is not to provide a detailed site-specific evaluation of the economics of water hyacinth utilisation but to demonstrate general principles. Any scheme that may be considered in a feasibility study will require to address the realities of the circumstance in which is to be based.

The production of fibre and fertiliser from the process is kept constant. These may be varied in schemes with managed growth to be a greater or lesser percentage of dry weight.

Scale sensitivity factors are also kept constant for all the spreadsheets studied. This is to prevent the over-complication of the financial pictures that will be produced.

Scales of application are defined by means of the biogas rate in cubic metres per day. For each scale-range to be considered a median is chosen and this is highlighted in bold. Output values above and below the median are calculated from input data. Costs are calculated according to the scale sensitivity factor, being the median scale cost times the scale up factor to the power of the sensitivity factor.

Columns "A" to "M" are used to calculated quantities and output values, columns "N" to "AA" provide a breakdown of costs for the various stages in the process and a comparison between costs and revenue. The 'bottom line' of the system is contained in columns "Z" and "AA".

Each of the values presented is linked into either inputs or outputs. There are numerous mathematical relationships involved in the spreadsheet involving simple algebra. No attempt is made to present this level of detail in this thesis. The intention has been to construct a tool for rapid evaluation of variables. Where one input or output value changes it is possible to see immediately what impact this will have upon system viability.

7.4.2 Small-scale systems

Bangladesh (Tables 7.1 and 7.2)

Taking the median of the small-scale operation as being 10 cubic metres of biogas per day, the quantity of water hyacinth to be harvested will be 400 kilogrammes per day, assuming that the productivity from each kilogramme is 420 litres. Where there is a 50% reduction in this output there will be a requirement for double this quantity.

Whilst a nominal rental is included for the growth area cost, in reality this will be a trivial sum in relation to the economics of the overall process. It is when harvesting, pre-treatment and digestion are covered that the real cost implications of a small-scale system become apparent. The quantities that are handled by human efforts are small in comparison to the costs of the labour time and capital requirements.

With the processes envisaged it will be essential, at a minimum, to have one semi-skilled person, able to resolve minor operational problems that may be encountered.

A further aspect of the small-scale scenario is the requirement for short paybacks. The payback period built into the spreadsheet is three years. If this is raised to seven years the overall system remains in the red. With a seven year payback the 10 cubic metre per day operation will produce a gross annual loss of £946 for an initial investment of £3,500 and an annual running cost of £1039.

By reducing labour costs to nil and capital costs to £500, giving an operating cost of nil (less capital costs), the median will produce an annual profit of £242. This is not a very exciting commercial prospect. Life in Bangladesh is very hard, with annual floods, monsoons and tidal waves affecting the lives of millions of people. It is not surprising to find that individual expectations for a return on effort is planned over

WATER HYACINTH UTILISATION IN BANGLADESH
COMMERCIAL ASSESSMENT
SMALL-SCALE

Gas produced by one dry weight kilogramme: CH_4 = 0.25 m3/kg : CO_2 = 0.17 m3/kg

Total gas production	0.42 m3/kg dry wt
Dry weight of plant	6%
Plant productivity	202 dry tonnes per hectare per annum (calc'd from growth seasons)

Cost = MSC x Scale up factor to the power "a"

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.03	0.9
Harvesting	2.14	0.9
Pretreatment	6.57	0.7
Digestion	6.37	0.7
Storage	0.00	0.8
Distribution	0.00	0.8
Total (£/t)	15.11	
Conversion to electricity (£/kW hr)	0.229	0.9

GROWTH SEASONS

Period of maximum growth	120 days	Maximum growth rate	0.75 kg dry matter per ha per day
Period of moderate growth	180 days	Moderate growth rate	0.55 kg dry matter per ha per day
Period of minimum growth	65 days	Minimum growth rate	0.20 kg dry matter per ha per day
Total growing time	365 days		

Output values

1 kW hr elec is valued at	£0.050
1 kW hr gas is valued at	£0.020
1 kg of fibre is valued at	£0.050
1 kg of NPK is valued at	£0.050

Conversion factors

1 kg wet WH produces	0.0168 kg of fibre.
1 kg wet WH produces	0.0060 kg of NPK fertiliser

Elect. generator availability	30%
Generator efficiency	25%

Percentage fertiliser sold: 100%

L=E+I+K M=G+I+K

A	B	C	D	E	F	G	H	I	J	K	L	M
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	Converted to electricity output (kW)	value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N,P,K t/yr) *#	Value of of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
3	0.12	0.01	0.73	128	0.18	24	0.74	37	0.26	13	178	74
10	0.40	0.04	2.43	426	0.61	80	2.45	123	0.88	44	592	246
30	1.2	0.13	7.3	1278	1.8	240	7.36	368	2.63	131	1,777	739
100	4	0.43	24.3	4258	6.1	798	24.53	1,226	8.76	438	5,923	2,463

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

V=P+Q+R+S+T+U X=V/L Y=(V+W)/M

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	Production cost gas/fertiliser/fibre (£/yr)	- electricity* (£/yr)	Ratio cost/revenue (Gas)	(Elect)	Annual gross profit Gas (£/yr)	Electricity* (£/yr)
3	0.12	1.5	106	413	400	0	0	920	124	5.180	14.131	(743)	(970)
10	0.40	4.3	313	959	930	0	0	2206	365	3.725	10.440	(1,614)	(2,325)
30	1.2	12	841	2069	2006	0	0	4928	982	2.773	7.998	(3,151)	(5,171)
100	4.0	34	2485	4807	4660	0	0	11,986	2,901	2.024	6.045	(6,063)	(12,424)

* Based on generating hrs per yr: 2628

Table 7.1

SMALL SCALE, MEDIAN RANGE, COST ANALYSIS
10 m3/day biogas ; 0.40 wet tonnes per day ; 0.04 ha ; 2.43 kW LCV ; 0.61 kWe

Total capital investment	£3,500 (Excluding generator)
Total annual running cost	£1,039 (Excluding generator and capital costs)

NOTES:

1 : Capital plant costs included on a simple	3
2 : Internally consummed electicity cost:	£0.050
3 : Working hours per annum	2503

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	0	0	0.000
Water area rental (£/ha)	100	4.34	0.030
Nutrient input		0	0.000
			0.030

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	1	313	2.143
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			2.143

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi-skilled labour	1	626	4.286
No. of skilled labour	0	0	0.000
Capital plant cost	£1,000	333	2.283
Power requirement (kW)	0	0	0.000
			6.569

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	£2,500	833	5.708
Power requirement (kW)	0.2	96	0.660
			6.368

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			0.000

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			0.000

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kw hr)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	£1,000	333	0.209
Operation/maintenance (£/kW hr)	£0.020	32	0.020
			0.229

Labour rates	Rate per day (£)
Unskilled labour	1.00
Semi skilled	2.00
Skilled	4.00
No of persons employed	2
Days of work per year	313

Table 7.2

WATER HYACINTH UTILISATION IN THAILAND
COMMERCIAL ASSESSMENT
MEDIUM-SCALE

Gas produced by one dry weight kilogramme: CH4 =		0.25 m3/kg : CO2 =	0.17 m3/kg
Total gas production	0.42 m3/kg dry wt		
Dry weight of plant	6%		
Plant productivity	202 dry tonnes per hectare per annum (calc'd from growth seasons)		

GROWTH SEASONS

Period of maximum growth	120 days	Maximum growth rate:	0.75 kg dry matter per ha per day
Period of moderate growth	180 days	Moderate grwoth rate:	0.55 kg dry matter per ha per day
Period of minimum growth	65 days	Minimum growth rate:	0.20 kg dry matter per ha per day
Total growing time	365 days		

Output values		**Conversion factors**	
1 kW hr elec is valued at	£0.050	1 kg wet WH produces	0.0168 kg of fibre.
1 kW hr gas is valued at	£0.020	1 kg wet WH produces	0.0060 kg of NPK fertiliser
1 kg of fibre is valued at	£0.050		
1 kg of NPK is valued at	£0.050		
Elect. generator availability	85%	Percentage fertiliser sold:	75%
Generator efficiency	30%		

Cost = MSC x Scale up factor to the power 'a'

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.23	0.9
Harvesting	0.38	0.9
Pretreatment	0.99	0.7
Digestion	1.65	0.7
Storage	0.54	0.8
Distribution	0.40	0.8
Total (£/t)	4.19	
Conversion to electricity (£/kW hr)	0.045	0.9

A	B	C	D	E	F	G	H	I	J	K	L=E+I+K	M=G+I+K
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	Converted to electricity output (kW)	Converted to electricity value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N,P,K t/yr)*#	Value of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
300	12	1.3	73	12775	22	8144	74	3679	20	985	17440	12809
1,000	40	4.3	243	42583	73	27147	245	12264	66	3285	58132	42696
3,000	120	13	729	127750	219	81441	736	36792	197	9855	174397	128088
10,000	400	43	2431	425833	729	271469	2453	122640	657	32850	581323	426959

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

V=P+Q+R+S+T+U X=V/L Y=(V+W)/M

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	Production cost gas/fertiliser/fibre (£/yr)	Production cost - electricity* (£/yr)	Ratio cost/revenue (Gas)	Ratio cost/revenue (Elect)	Annual gross profit Gas (£/yr)	Annual gross profit Electricity (£/yr)
300	12	1140	1651	6234	10350	3019	2256	24651	8251	1.41	2.57	-7211	-20093
1000	40	3370	5503	14481	24042	7911	5911	61217	24384	1.05	2.00	-3084	-42905
3000	120	9059	16509	31245	51874	19051	14234	141971	65541	0.81	1.62	32426	-79424
10,000	400	26770	55029	72575	120493	49913	37294	362075	193689	0.62	1.30	219248	-128806

* Based on generating hrs per yr: 7446

Table 7.3

MEDIUM-SCALE, MEDIAN-RANGE COST ANALYSIS
1,000 m3/day biogas ; 40 wet tonnes per day ; 434 ha ; 243 kW LCV ; 73 kWe

NOTES:
1 : Capital plant costs included on a simple 5 year payback
2 : Internally consummed electicity cost: £0 050
3 : Working hours per annum 2503

Total capital investment £140,000 (Excluding generator)

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	2	2503	0.171
Water area rental (£/ha)	200	867 33	0.059
Nutrient input		0	0.000
			0 231

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	2	2503	0 171
Capital plant cost	£15,000	3000	0 205
Power requirement (kW)	0 0	0	0 000
			0 377

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi-skilled labour	2	4693	0 321
No. of skilled labour	1	3911	0 268
Capital plant cost	£20,000	4000	0 274
Power requirement (kW)	15.0	1877	0.129
			0 992

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	2	4693	0 321
Skilled labour	1	3911	0 268
Capital plant cost	£75,000	15000	1 027
Power requirement (kW)	1 0	438	0 030
			1 647

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	1	2346	0.161
Skilled labour	1	3911	0 268
Capital plant cost	£20,000	4000	0 274
Power requirement (kW)	0 00	0	0.000
			0.542

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	1	2346	0 161
Skilled labour	1	3911	0 268
Capital plant cost	£10,000	2000	0 137
Power requirement (kW)	0 00	0	0 000
			0 405

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kw hr)
Semi-skilled labour	1	2340	0.004
Skilled labour	1	3900	0 007
Capital plant cost	£50,000	10000	0.018
Operation/maintenance (£/kW hr)	£0.015	8144	0.015
			0.045

Labour rates	Rate per day (£)
Unskilled labour	4 00
Semi skilled	7 50
Skilled	12 50
No of persons employed	16
Days of work per year	313

Table 7.4

a very short interval. The possibility of a small farmer entering into a two year payback cycle involving such comparatively large capital costs is an unrealistic proposition. This situation is further complicated by the fact that it will be extremely unlikely that a viable system can be built for £500.

The revenue streams generated by a considerable amount of effort are very weak. The gas system revenue is £592, and this assumes that a market can be found for small volumes of fibre and fertiliser. Where gas is used to generate electricity the effect is to reduce revenue. This is a problem commonly encountered by all small scale generation schemes. The operational costs involved make the income requirements much greater than a small-scale system can generate.

Thailand (Tables 7.3 and 7.4)

The situation for small-scale use of water hyacinth is very much worse in Thailand. All costs are in general about fifty percent greater resulting in a hopeless commercial prospect.

7.4.3 Medium-scale systems

It is with the consideration of medium-scale operations that the commercial opportunity begins to become attractive.

Bangladesh (Tables 7.5 and 7.6)

Looking at a system with a daily biogas production rate of 1,000 cubic metres, there will be a requirement for a daily harvest of 40 wet tonnes of plant material. It is assumed that the production from each dry kilogramme of harvested plant will be 420 litres of biogas. Once capital expenditure reaches the levels involved with even medium scale systems it will be essential to overcome the remaining obstacles to maximising output from the juicing/high-rate process route.

For a total capital investment of approximately £100,000, an annual running cost of around £13,000 and a payback of 5 years, the system will generate a gross annual profit of about £28,000. Once again this is not an exciting commercial proposition as it stands but it has the seeds of an opportunity that can be engineered into a more favourable position by minimising capital expenditure, through design optimisation and improved efficiency. The system as envisaged employs sixteen people.

The electricity generation option only just manages to break even in this range. With 73 kW of electricity it is still not a realistic venture to install

WATER HYACINTH UTILISATION IN BANGLADESH
COMMERCIAL ASSESSMENT
MEDIUM-SCALE

Cost = MSC x Scale up factor to the power "a"

Gas produced by one dry weight kilogramme: CH_4 =		0.25 m3/kg : CO_2 =	0.17 m3/kg
Total gas production	0.42 m3/kg dry wt		
Dry weight of plant	6%		
Plant productivity	(202)dry tonnes per hectare per annum (calc'd from growth seasons)		

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.07	0.9
Harvesting	0.18	0.9
Pretreatment	0.51	0.7
Digestion	0.89	0.7
Storage	0.29	0.8
Distribution	0.15	0.8
Total (£/t)	2.09	
Conversion to electricity (£/kW hr)	0.037	0.9

GROWTH SEASONS

Period of maximum growth	(120)days	Maximum growth rate:	0.75 kg dry matter per ha per day
Period of moderate growth	(180)days	Moderate grwoth rate:	0.55 kg dry matter per ha per day
Period of minimum growth	(65)days	Minimum growth rate:	0.20 kg dry matter per ha per day
Total growing time	(365)days		

Output values		**Conversion factors**	
1 kW hr elec is valued at	£0.050	1 kg wet WH produces	0.0168 kg of fibre.
1 kW hr gas is valued at	£0.020	1 kg wet WH produces	0.0060 kg of NPK fertiliser
1 kg of fibre is valued at	£0.050		
1 kg of NPK is valued at	£0.050		
Elect. generator availability	85%	Percentage fertiliser sold:	75%
Generator efficiency	30%		

A	B	C	D	E	F	G	H	I	J	K	L	M
											L=E+I+K	M=G+I+K
					Converted to electricity							
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	output (kW)	value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N,P,K t/yr)*#	Value of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
300	12	1.3	73	12775	22	8144	74	3679	20	985	17440	12809
1,000	40	4.3	243	42583	73	27147	245	12264	66	3285	58132	42696
3,000	120	13	729	127750	219	81441	736	36792	197	9855	174397	128088
10,000	400	43	2431	425833	729	271469	2453	122640	657	32850	581323	426959

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
								V=P+Q+R+S+T+U		X=V/L	Y=(V+W)/M		
								Production cost		Ratio cost/revenue		Annual gross profit	
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	gas/fertiliser/fibre (£/yr)	electricity* (£/yr)	(Gas)	(Elect)	Gas (£/yr)	Electricity (£/yr)
(300)	12	358	788	3177	5571	1623	859	12377	6773	0.71	1.50	5063	-6341
(1000)	40	1059	2626	7380	12941	4251	2251	30509	20016	0.52	1.18	27624	-7829
(3000)	120	2847	7877	15924	27922	10238	5422	70231	53801	0.40	0.97	104166	4056
10,000	400	8415	26257	36988	64858	26825	14206	177548	158993	0.31	0.79	403775	90418

* Based on generating hrs per yr: (7446)

Table 7.5

MEDIUM-SCALE, MEDIAN-RANGE COST ANALYSIS
1,000 m3/day biogas ; 40 wet tonnes per day ; 434 ha ; 243 kW LCV ; 73 kWe

Total capital investment	£95,000 (Excluding generator)
Total annual running cost	£12,760 (Excluding generator and capital costs)

NOTES:

1 : Capital plant costs included on a simple	(5)year payback
2 : Internally consummed electicity cost:	£0.050
3 : Working hours per annum	(2503)

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	(2)	(626)	0.043
Water area rental (£/ha)	(100)	433.66	0.030
Nutrient input		(0)	0.000
			0.073

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	(2)	(626)	0.043
Capital plant cost	£10,000	(2000)	0.137
Power requirement (kW)	0.0	(0)	0.000
			0.180

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi-skilled labour	(2)	(1251)	0.086
No. of skilled labour	(1)	(1251)	0.086
Capital plant cost	£15,000	(3000)	0.205
Power requirement (kW)	15.0	(1877)	0.129
			0.505

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	(2)	(1251)	0.086
Skilled labour	(1)	(1251)	0.086
Capital plant cost	£50,000	(10000)	0.685
Power requirement (kW)	1.0	(438)	0.030
			0.886

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	(1)	(626)	0.043
Skilled labour	(1)	(1251)	0.086
Capital plant cost	(15000)	(3000)	0.205
Power requirement (kW)	0.00	(0)	0.000
			0.291

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	(1)	(626)	0.043
Skilled labour	(1)	(1251)	0.086
Capital plant cost	£5,000	(1000)	0.068
Power requirement (kW)	0.00	(0)	0.000
			0.154

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kw hr)
Semi skilled labour	(1)	(624)	0.001
Skilled labour	(1)	(1248)	0.002
Capital plant cost	£50,000	(10000)	0.018
Operation/maintenance (£/kW hr)	£0.015	(8144)	0.015
			0.037

Labour rates	Rate per day (£)
Unskilled labour	1.00
Semi skilled	2.00
Skilled	4.00
No of persons employed	(16)
Days of work per year	(313)

Table 7.6

WATER HYACINTH UTILISATION IN THAILAND
COMMERCIAL ASSESSMENT
SMALL-SCALE

Cost = MSC x Scale up factor to the power "a"

Gas produced by one dry weight kilogramme: CH_4 =		0.25 m3/kg : CO_2 =	0.17 m3/kg
Total gas production	0.42 m3/kg dry wt		
Dry weight of plant	6%		
Plant productivity	202 dry tonnes per hectare per annum (calc'd from growth seasons)		

GROWTH SEASONS

Period of maximum growth	120 days	Maximum growth rate	0.75 kg dry matter per ha per day
Period of moderate growth	180 days	Moderate growth rate	0.55 kg dry matter per ha per day
Period of minimum growth	65 days	Minimum growth rate	0.20 kg dry matter per ha per day
Total growing time	365 days		

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.06	0.9
Harvesting	8.57	0.9
Pretreatment	19.50	0.7
Digestion	7.51	0.7
Storage	0.00	0.8
Distribution	0.00	0.8
Total (£/t)	**35.64**	
Conversion to electricity (£/kW hr)	0.333	0.9

Output values

1 kW hr elec is valued at	£0.050
1 kW hr gas is valued at	£0.020
1 kg of fibre is valued at	£0.050
1 kg of NPK is valued at	£0.050

Conversion factors

1 kg wet WH produces	0.0168 kg of fibre.
1 kg wet WH produces	0.0060 kg of NPK fertiliser

Elect. generator availability	30%
Generator efficiency	25%
Percentage fertiliser sold:	100%

A	B	C	D	E	F	G	H	I	J	K	L	M
											L=E+I+K	M=G+I+K
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	Converted to electricity output (kW)	Converted to electricity value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N,P,K t/yr) *#	Value of of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
3	0.12	0.01	0.73	128	0.18	24	0.74	37	0.26	13	178	74
10	0.40	0.04	2.43	426	0.61	80	2.45	123	0.88	44	592	246
30	1.2	0.13	7.3	1278	1.8	240	7.36	368	2.63	131	1,777	739
100	4	0.43	24.3	4258	6.1	798	24.53	1,226	8.76	438	5,923	2,463

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
								V=P+Q+R+S+T+U		X=V/L	Y=(V+W)/M		
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	Production cost gas/fertiliser/fibre (£/yr)	Production cost - electricity* (£/yr)	Ratio cost/revenue (Gas)	Ratio cost/revenue (Elect)	Annual gross profit Gas (£/yr)	Annual gross profit Electricity* (£/yr)
3	0.12	2.9	423	1225	472	0	0	2124	180	11.953	31.181	(1,946)	(2,230)
10	0.40	8.7	1251	2846	1096	0	0	5203	532	8.785	23.285	(4,611)	(5,489)
30	1.2	23	3364	6142	2366	0	0	11894	1,430	6.694	18.033	(10,117)	(12,585)
100	4.0	69	9940	14266	5495	0	0	29,770	4,225	5.026	13.803	(23,847)	(31,533)

* Based on generating hrs per yr: 2628

Table 7.7

SMALL-SCALE, MEDIAN RANGE, COST ANALYSIS
10 m3/day biogas ; 0.40 wet tonnes per day ; 0.04 ha ; 2.43 kW LCV ; 0.61 kWe

Total capital investment £4 500 (Excluding generator)

NOTES:
1 : Capital plant costs included on a simple 3 year payback
2 : Internally consummed electicity cost: £0 050
3 : Working hours per annum 2503

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	0	0	0.000
Water area rental (£/ha)	200	8.67	0.059
Nutrient input		0	0.000
			0.059

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	1	1251	8.571
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			8.571

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi skilled labour	1	2346	16.071
No. of skilled labour	0	0	0.000
Capital plant cost	£1,500	500	3.425
Power requirement (kW)	0	0	0.000
			19.496

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	£3,000	1000	6.849
Power requirement (kW)	0.2	96	0.660
			7.509

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			0.000

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	0	0	0.000
Power requirement (kW)	0	0	0.000
			0.000

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kW hr)
Semi skilled labour	0	0	0.000
Skilled labour	0	0	0.000
Capital plant cost	£1,500	500	0.313
Operation/maintenance (£/kW hr)	£0.020	32	0.020
			0.333

Labour rates	Rate per day (£)
Unskilled labour	4.00
Semi skilled	7.50
Skilled	12.50
No of persons employed	2
Days of work per year	313

Table 7.8

such a capability. At 210 kW the system begins to make money, but still considerably less than that which can be earned by selling or valuing gas for direct-burn applications.

As with small-scale systems, the viability of the whole operation is tied in with the ability to value both fibre and fertiliser as products. Should this not be the case in any particular situation the impact will be to significantly reduce gross profit, though not to render the systems loss-making.

Thailand (Tables 7.7 and 7.8)

The median for a medium-scale system in Thailand is still not viable. It is probable that only large scale utilisation will be commercial in such an economic setting as prevails in this country.

7.4.4 Large-scale systems

It is in the setting of large-scale applications that the utilisation of water hyacinth becomes attractive. The reduction in costs per unit of material handled and, consequently, of product output costs is dramatic.

Bangladesh (Table 7.9 and 7.10)

With a daily biogas flow rate of 100,000 cubic metres, a daily feedstock requirement of 4,000 tonnes and a payback of seven years, a capital investment of £5,000,000, with an associated running cost of £556,000, will produce a gross profit of about £3,500,000. Of this £600,000 will be drawn from selling fibre and £110,000 from selling fertiliser. The system will employ eighty-five people and will be able to pay, as is the norm for sophisticated industrial operations in developing countries, about fifty percent above the standard commercial wage in order to secure better quality personnel.

It is interesting to note that the value of electricity generated will be less than that of direct gas sales. The problem with gas sales, even at this scale of operation is that the presence of a continuous base load customer is often difficult to secure. Gas storage and load buffering then become important and these will have a negative impact upon the system economics. It is in such situations that electricity generation comes into its own. In most countries of the world there exists a

WATER HYACINTH UTILISATION IN BANGLADESH
COMMERCIAL ASSESSMENT
LARGE-SCALE

Gas produced by one dry weight kilogramme: CH_4 =		0.25 m3/kg : CO_2 =	0.17 m3/kg	
Total gas production	0.42 m3/kg dry wt			
Dry weight of plant	6%			
Plant productivity	202 dry tonnes per hectare per annum (calc'd from growth seasons)			
GROWTH SEASONS				
Period of maximum growth	120 days	Maximum growth rate	0.75 kg dry matter per ha per day	
Period of moderate growth	180 days	Moderate growth rate	0.55 kg dry matter per ha per day	
Period of minimum growth	65 days	Minimum growth rate	0.20 kg dry matter per ha per day	
Total growing time	365 days			
Output values		**Conversion factors**		
1 kW hr elec is valued at	£0.050	1 kg wet WH produces	0.0168 kg of fibre.	
1 kW hr gas is valued at	£0.020	1 kg wet WH produces	0.0060 kg of NPK fertiliser	
1 kg of fibre is valued at	£0.025			
1 kg of NPK is valued at	£0.025			
Elect. generator availability	97%	Percentage fertiliser sold:	50%	
Generator efficiency	37%			

Cost = MSC x Scale up factor to the power "a"

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.03	0.9
Harvesting	0.01	0.9
Pretreatment	0.12	0.7
Digestion	0.56	0.7
Storage	0.09	0.8
Distribution	0.06	0.8
Total (£/t)	0.87	
Conversion to electricity (£/kW hr)	0.014	0.9

A	B	C	D	E	F	G	H	I	J	K	L	M
											L=E+I+K	M=G+I+K
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	Converted to electricity output (kW)	value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N.P.K.t/yr)*#	Value of of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
30,000	1,200	130	7,292	1,277,500	2,698	1,146,237	7,358	183,960	1,314	32,850	1,494,310	1,363,047
100,000	4,000	434	24,306	4,258,333	8,993	3,820,790	24,528	613,200	4,380	109,500	4,981,033	4,543,490
300,000	12,000	1,301	72,917	12,775,000	26,979	11,462,369	73,584	1,839,600	13,140	328,500	14,943,100	13,630,469
1,000,000	40,000	4,337	243,056	42,583,333	89,931	38,207,896	245,280	6,132,000	43,800	1,095,000	49,810,333	45,434,896

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
								V=P+Q+R+S+T+U		X=V/L	Y=(V+W)/M		
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	Production cost gas/fertiliser/fibre (£/yr)	- electricity* (£/yr)	Ratio cost/revenue (Gas)	(Elect)	Annual gross profit Gas (£/yr)	Electricity (£/yr)
30,000	1,200	14,418	6,643	50,929	351,965	48,211	32,731	504,896	366,504	0.34	0.64	989,414	491,647
100,000	4,000	48,059	19,631	169,763	817,550	126,314	85,754	1,267,071	1,083,102	0.25	0.52	3,713,962	2,193,316
300,000	12,000	144,178	52,765	509,289	1,764,003	304,193	206,516	2,980,942	2,911,244	0.20	0.43	11,962,158	7,738,282
1,000,000	40,000	480,592	155,932	1,697,629	4,097,456	796,989	541,073	7,769,671	8,603,388	0.16	0.36	42,040,662	29,061,836

* Based on operating hrs per yr: 8,497

Table 7.9

LARGE-SCALE, MEDIAN RANGE COST ANALYSIS
100,000 m3/day biogas ; 4,000 wet tonnes per day ; 434 ha ; 24,306 kW LCV ; 7,292 kWe

Total capital investment	£5,075,000	(Excluding generator)
Total annual running cost	£556,111	(Excluding generator and capital costs)

NOTES:

1 : Capital plant costs included on a simple		7 year payback
2 : Internally consummed electicity cost:	£0.050	
3 : Working hours per annum	2,503	

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	10	4,693	0.003
Water area rental (£/ha)	100	43366.34	0.030
Nutrient input		0	0.000
			0.033

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	15	7,039	0.005
Capital plant cost	£75,000	10,714	0.007
Power requirement (kW)	15.0	1,877	0.001
			0.013

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi-skilled labour	10	9,386	0.006
No. of skilled labour	5	15,643	0.011
Capital plant cost	£1,000,000	142,857	0.098
Power requirement (kW)	15.0	1,877	0.001
			0.116

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	5	4,693	0.003
Skilled labour	2	6,257	0.004
Capital plant cost	£3,500,000	500,000	0.342
Power requirement (kW)	700.0	306,600	0.210
			0.560

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	10	9,360	0.006
Skilled labour	15	46,800	0.032
Capital plant cost	250,000	35,714	0.024
Power requirement (kW)	100.00	43,800	0.030
			0.087

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	5	4,680	0.003
Skilled labour	2	6,240	0.004
Capital plant cost	£250,000	35,714	0.024
Power requirement (kW)	100.00	43,800	0.030
			0.059

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kw hr)
Semi-skilled labour	4	3,744	0.000
Skilled labour	2	6,240	0.000
Capital plant cost	£3,500,000	500,000	0.007
Operation/maintenance (£/kW hr)	£0.008	573,118	0.008
			0.014

Labour rates	Rate per day (£)
Unskilled labour	1.50
Semi skilled	3.00
Skilled	10.00
No of persons employed	85
Days of work per year	313

Table 7.10

WATER HYACINTH UTILISATION IN THAILAND
COMMERCIAL ASSESSMENT
LARGE-SCALE

Gas produced by one dry weight kilogramme: CH_4 =	0.25 m3/kg : CO_2 =	0.17 m3/kg	
Total gas production	0.42 m3/kg dry wt		
Dry weight of plant	6%		
Plant productivity	202 dry tonnes per hectare per annum (calc'd from growth seasons)		

GROWTH SEASONS

Period of maximum growth	120 days	Maximum growth rate	0.75 kg dry matter per ha per day
Period of moderate growth	180 days	Moderate growth rate	0.55 kg dry matter per ha per day
Period of minimum growth	65 days	Minimum growth rate	0.20 kg dry matter per ha per day
Total growing time	365 days		

Output values		Conversion factors	
1 kW hr elec is valued at	£0.050	1 kg wet WH produces	0.0168 kg of fibre.
1 kW hr gas is valued at	£0.020	1 kg wet WH produces	0.0060 kg of NPK fertiliser
1 kg of fibre is valued at	£0.025		
1 kg of NPK is valued at	£0.025		
Elect. generator availability	97%	Percentage fertiliser sold:	50%
Generator efficiency	37%		

Cost = MSC x Scale up factor to the power "a"

	Median scale cost (MSC) (£/t)	Scale sensitivity factor (a)
Growth	0.04	0.9
Harvesting	0.02	0.9
Pretreatment	0.13	0.7
Digestion	0.71	0.7
Storage	0.10	0.8
Distribution	0.06	0.8
Total (£/t)	1.08	
Conversion to electricity (£/kW hr)	0.014	0.9

A	B	C	D	E	F	G	H	I	J	K	L	M
											L=E+I+K	M=G+I+K
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Growing area (ha) +	LCV of gas (kW)	Value of gas (£/yr) *	Converted to electricity output (kW)	Converted to electricity value (£/yr) *	Quantity of fibre (t/yr) *	Value of fibre (£/yr) *	Quantity of fertiliser (N.P.K t/yr)*#	Value of fertiliser (£/yr) *	Gas system revenue (£/yr) *	Electrical system revenue (£/yr) *
30,000	1,200	130	7,292	1,277,500	2,698	1,146,237	7,358	183,960	1,314	32,850	1,494,310	1,363,047
100,000	4,000	434	24,306	4,258,333	8,993	3,820,790	24,528	613,200	4,380	109,500	4,981,033	4,543,490
300,000	12,000	1,301	72,917	12,775,000	26,979	11,462,369	73,584	1,839,600	13,140	328,500	14,943,100	13,630,469
1,000,000	40,000	4,337	243,056	42,583,333	89,931	38,207,896	245,280	6,132,000	43,800	1,095,000	49,810,333	45,434,896

* Based upon total growing time
\# Modified by percentage sold
\+ Based upon total annual plant productivity

COMPARISON OF COSTS AND REVENUE

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
								V=P+Q+R+S+T+U		X=V/L	Y=(V+W)/M		
Biogas rate (m3/day)	Feedstock rate (wet t/day)	Cost of growth (£/yr)	Cost of harvesting (£/yr)	Cost of pretreatment (£/yr)	Cost of digestion (£/yr)	Cost of storage (£/yr)	Cost of distribution (£/yr)	Production cost gas/fertiliser/fibre (£/yr)	Production cost - electricity* (£/yr)	Ratio cost/revenue (Gas)	Ratio cost/revenue (Elect)	Annual gross profit Gas (£/yr)	Annual gross profit Electricity (£/yr)
30,000	1,200	17,703	12,201	58,437	449,268	57,143	33,921	628,673	369,882	0.42	0.73	865,637	364,492
100,000	4,000	59,009	36,056	194,791	1,043,568	149,714	88,874	1,572,013	1,093,086	0.32	0.59	3,409,021	1,878,390
300,000	12,000	177,028	96,913	584,374	2,251,674	360,546	214,029	3,684,564	2,938,080	0.25	0.49	11,258,536	7,007,824
1,000,000	40,000	590,092	286,401	1,947,914	5,230,229	944,633	560,759	9,560,028	8,682,694	0.19	0.40	40,250,305	27,192,174

* Based on operating hrs per yr: 8,497

Table 7.11

LARGE-SCALE, MEDIAN-RANGE COST ANALYSIS
100,000 m3/day biogas ; 4,000 wet tonnes per day ; 434 ha ; 24,306 kW LCV ; 7,292 kWe

Total capital investment £6,575,000 (Excluding generator)

NOTES:
1 : Capital plant costs included on a simple 7 year payback
2 : Internally consummed electicity cost: £0 050
3 : Working hours per annum 2,503

GROWTH		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	10	15,643	0 011
Water area rental (£/ha)	100	43366 34	0 030
Nutrient input		0	0.000
			0 040

HARVESTING		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of unskilled labour	15	23,464	0 016
Capital plant cost	£75,000	10,714	0 007
Power requirement (kW)	15 0	1,877	0 001
			0 025

PRETREATMENT		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
No. of semi-skilled labour	10	26,593	0 018
No. of skilled labour	5	23,464	0 016
Capital plant cost	£1,000,000	142,857	0.098
Power requirement (kW)	15 0	1,877	0 001
			0 133

DIGESTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	5	13,296	0 009
Skilled labour	2	9,386	0 006
Capital plant cost	£5,000,000	714,286	0 489
Power requirement (kW)	700 0	306 600	0 210
			0 715

STORAGE		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	10	26,520	0 018
Skilled labour	15	70,200	0 048
Capital plant cost	250,000	35,714	0 024
Power requirement (kW)	100 00	43,800	0 030
			0 103

DISTRIBUTION		Estimated cost (£/yr)	Cost per tonne wet weight (£/t)
Semi-skilled labour	5	13,260	0 009
Skilled labour	2	9,360	0 006
Capital plant cost	£250,000	35,714	0 024
Power requirement (kW)	100 00	43,800	0 030
			0 061

CONVERSION TO ELECTRICITY		Estimated cost (£/yr)	Cost per unit (£/kw hr)
Semi-skilled labour	4	10,608	0 000
Skilled labour	2	9,360	0 000
Capital plant cost	£3,500,000	500,000	0 007
Operation/maintenance (£/kW hr)	£0 008	573,118	0 008
			0 014

Labour rates	Rate per day (£)
Unskilled labour	5 00
Semi skilled	8 50
Skilled	15 00
No of persons employed	85
Days of work per year	313

Table 7.12

distribution network for electricity and the presence of an additional seven megawatts in such systems will not cause difficulty for most networks. Careful planning will ensure that all the electricity generated will be subject to immediate transfer and sale.

Large-scale systems will of necessity have to be built with the concept of cultivation clearly built into growth of the plant. Harvesting 40,000 tonnes per day cannot be left to the vagaries of wild growth. This being the case, it will be possible to facilitate the harvesting function by arranging plants to pass over a weir and through an inclined mesh system so that water passes through and biomass is taken off, at a steady rate, for use. Such an arrangement would reduce energy costs for harvesting to nil. There will be a requirement to manage flow rates but this can be accomplished by monitoring flow rates in versus rate of plant harvesting and adjusting the former with inflow gates. Such additional complexity will be minor compared to that which would be required in a large-scale system where a mechanical harvesting system were employed.

Thailand (Table 7.11 and 7.12)

In the case of Thailand, gross profit is marginally down on that which may be achieved in Bangladesh, but not to a point where the system is any less attractive commercially.

7.5 SENSITIVITY

Whilst the selection of values for the various variables that are implied in the foregoing discussions has been based upon data from the two countries of interest there is, almost inevitably, a high probability that these will not be accurate for any length of time. Combined with this uncertainty is a requirement to assess viability in terms of varied input and output values. The points in the system that most heavily influence commercial viability should be addressed as a priority.

The following section discusses the sensitivity of key parameters to change and draws preliminary conclusions from this work.

7.5.1 Revenue/cost ratio vs throughput

The revenue to cost ratio (RCR) provides a useful indication of the viability of a particular scheme. Where the ratio is less than one, the scheme is costing more than it is earning. Where it is greater than one the scheme is showing a return. It should be remembered that factors such as overheads and tax have not been allowed for in the model as

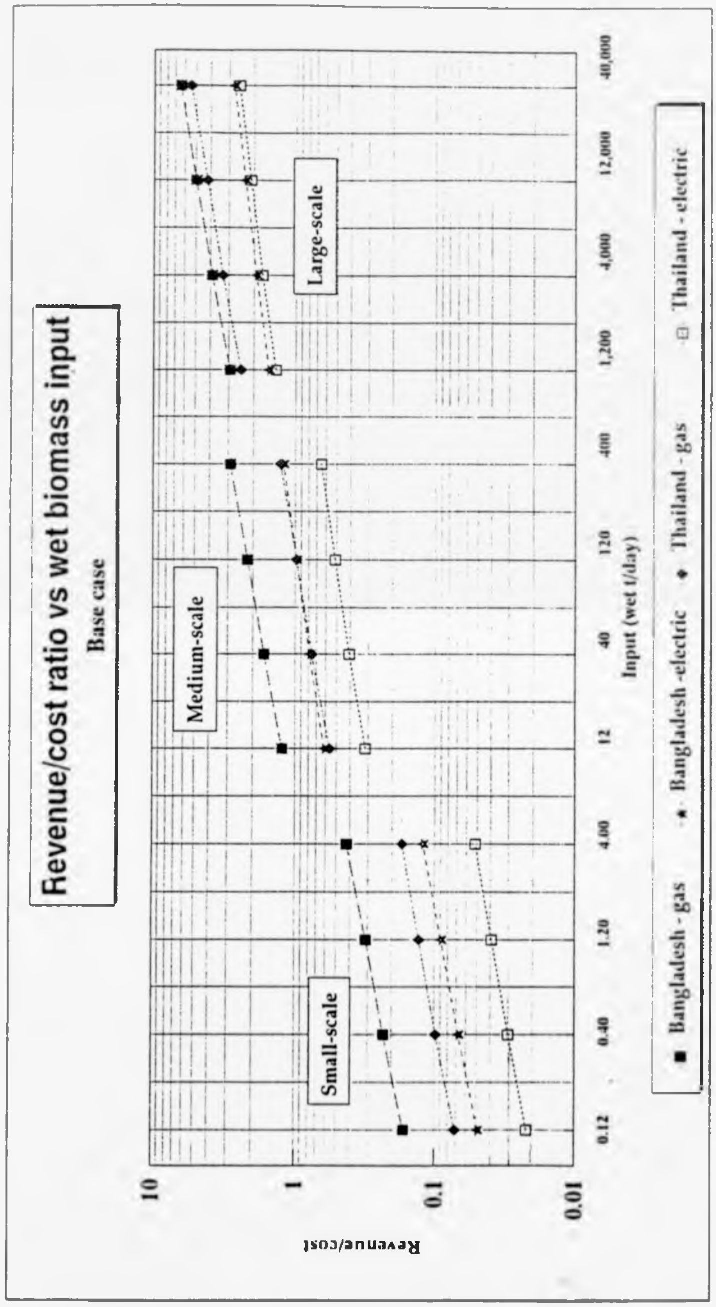


Figure 7.1 Revenue/cost ratio analysis

it stands. This analysis, therefore, provides an initial evaluation by which the comparatively more attractive and clearly non-viable schemes may be separated.

The data is presented in the form of graphs to facilitate ready appreciation of the relative values. It should be noted that the discontinuities which occur result from the transition from one scale to another, eg "small" to "medium". Tabulated results, as well as base-case input values, are included in Appendix 4. These show the base case RCR and the effect on the RCR of, respectively, a 100% increase in a designated parameter above its base case value and a 50% decrease in the same parameter below the base case value. A sensitivity analysis is also performed on the same variables, calculating the fractional change in the RCR resulting from a change in a parameter divided by the change in that parameter. A graphical presentation of the sensitivity analysis is also included after the tabulated results. The sensitivity figures are based upon a 1% increase and a 1% decrease in an individual variable.

As can be seen in Figure 7.1, the base case analysis of the RCR vs wet biomass input, all the schemes considered under the heading of small-scale (0.12-4 tonnes wet biomass input per day) do not produce a net profit. The best that can be managed is a ratio of 0.43, indicating that the revenue is 43% of the cost. As will be seen in the subsequent discussion of sensitivity, this situation can only be significantly altered by removing capital and labour costs. Unlike the use of cattle waste or sewage to produce biogas, there is little social benefit gained from disposing of water hyacinth to which an added value could be ascribed. It may be that national clean-up programmes will be implemented, offering financial incentives for the collection of water hyacinth. Such a possibility is rather remote and has not been included in the current evaluation.

The large-scale use of water hyacinth (1,200-4,000 tonnes wet biomass input per day) would appear to be viable in both countries for the production of both gas and electricity. Gas production in Bangladesh and Thailand produces RCR's ranging from 1.26 (Thailand, 400 t/day) to 6.07 (Bangladesh, 40,000 t/day). This latter figure is dramatic and demonstrates the significant advantages that can be obtained from economies of scale.

Medium-scale use of water hyacinth (12-400 tonnes wet biomass input per day) produces a range of ratios crossing the break-even line. The production of gas in Bangladesh is viable throughout the range. The production of gas in Thailand only becomes viable when the input reaches 400 tonnes per day. The medium-scale production of electricity in Thailand would not appear to be viable. Labour costs are higher than in Bangladesh and, as there is a significant labour input required for medium-scale schemes, this means that viability cannot be attained. With the approach of 'newly industrialised' status for Thailand it is unlikely that a high labour-input scenario will ever be viable. The situation in Bangladesh, however, is almost the reverse, with an extremely poor country actually declining in 'wealth'. High labour utilisation rates are, therefore, a source of potential social and commercial benefit.

7.5.2 Sensitivity of revenue/cost ratio to input variables

Of particular interest, especially with regard to medium-scale systems, is the sensitivity of the RCR to costs and income. Where an increase in the RCR can be achieved the possibility of smaller-throughput schemes becoming viable is increased. The following section analyses in broad terms the sensitivity of the various scales considered here. Input costs are considered first, followed by variations in the revenue available from the sale of the various output streams.

Framework for analysis

Whilst based upon data collected in the field, a great many assumptions have been made with regard to the costs of various inputs and the value of the product streams. The production of fibre from water hyacinth, for example, may cause an existing fibre market to loose its value. Alternatively, the generation of electricity from water hyacinth derived fuels may attract a premium payment from the government in recognition of its contribution to the environment in general, as is presently the case for renewable energy sources in the UK. In order to assess the impact of such potentially large changes in base-case input and output values two approaches have been taken.

The first is to consider directly the impact upon the RCR of comparatively large changes in base data. Each input value is varied by plus 100% and minus 50%. These variations are tabulated in Appendix 4. In each case they are also graphically presented, separately for Thailand and Bangladesh. The base-case graph is repeated above each set of graphs for ease of comparison. By this means it is possible to see immediately how such changes will effect the RCR and, therefore, the system viability.

The second method of assessing the system economics is to calculate the sensitivity of each throughput considered to changes in the input values. This provides a comparative assessment from which the inputs of greater sensitivity can be determined. It is by working to improve the efficiency of the areas of greater sensitivity that improvements can be made in the overall RCR of actual schemes. For the purpose of this study values of plus and minus 1% have been employed.

It is important to note that sensitivities across scales, eg from medium to large, are not valid . The composition of the input assumptions varies from scale to scale. In the small-scale, for example, the use of manual labour is paramount whereas in the large-scale labour forms a smaller part of operational costs. The medium-scale is a mixture of labour and energy inputs and, therefore, responds differently, yet again, to changes in labour costs.

Global costs

Under the heading of global costs are considered land rental, labour and capital. Land rental has a very low sensitivity rating, for all three scales, indicating that this is not a key component. Water space is of low value when compared to agricultural land. Labour and capital costs, however, contribute to a significantly to the make up of schemes. For small-scale it is interesting to note that even with a 50% reduction in capital costs none of the considered throughput approaches anywhere near to viability. The same is observed when labour costs are halved.

It is with medium-scale systems that the influence of large input changes is most marked. Where labour rates double there is a consequent depression of the point at which viability is achieved in Bangladesh. Similarly, by reducing capital costs by 50% the possibility of gas production becomes apparent in Thailand.

As with the graph of RCR against throughput, the sensitivity analysis performed with a 1% increase in costs, demonstrates that of the global factors influencing viability, the matter of capital cost is paramount with a sensitivity of around 0.6. Whilst labour rates will effect the viability of schemes there is little can be done to influence such social matters. The nominal day rates applied in the model are higher for the large-scale schemes (sensitivity = 0.1) than for small-scale (sensitivity = 0.45) and yet sensitivity is much less. This would indicate that there is more scope for paying higher labour rates with large-scale projects. By contrast, capital costs have a fairly constant effect upon economics, across all three scales (sensitivity = 0.6).

Process costs

Process costs include growth, harvesting, pre-treatment, digestion, storage and distribution. Of these the dominant costs are incurred in pre-treatment and digestion (sensitivity = 0.5 for small and medium-scale in Bangladesh and around 1 for large scale in both Bangladesh and Thailand). In this thesis digestion is seen as an area of major importance. Clearly, work to reduce such costs will have a significant impact on commercial performance. By contrast the costs of digestion are less significant for the small and medium-scale. The parallel between capital and digester costs on viability is worthy of note. In the base-case only gas production in Bangladesh is clearly viable in the medium-scale. With a 50% reduction in digester costs there is also the possibility of viable electricity production. Such a reduction, however, still leaves the medium-scale unattractive for Thailand.

To some extent, pre-treatment is the converse of digestion in terms of sensitivity. In the small-scale system viability is highly sensitive to changes in pre-treatment costs (sensitivity = 0.45), whereas in the large-scale it is less so (sensitivity = 0.2). By mechanising pre-treatment in large-scale systems and reducing the labour input the sensitivity to this aspect is reduced.

Output prices

As may be anticipated, the effect of doubling or halving revenue from individual outputs is dramatic. Despite this effect, it is notable that even with a doubling of the gas price the small-scale RCR does not rise above 1 for either Bangladesh or Thailand. The same is true of fibre, fertiliser and electricity. A doubling of the gas price will, however, result in gas production becoming viable in Thailand.

7.5.3 Conclusions

In reality the above single parameter variations will not occur. It may well be that, for example, labour rates will increase, capital costs will decrease and the overall costs for digestion will also decrease. A severe combination of cost improvements, however, will be required to lift the small-scale above an RCR of 1. In view of this it is difficult to see how small-scale applications can ever realistically be made viable without some form of massive intervention from the state.

Digestion is a dominant theme through all three scales and, as mentioned previously, one which would merit from additional research and development. The costs employed in the economic model are based upon research work undertaken as part of this thesis, where reductions in retention time lead to reduced capital costs. The scope for additional work to increase digestion rates, perhaps with the assistance of micro-biologists, is one that remains.

An overriding conclusion is that large-scale applications will be commercially attractive and robust. Even with a 50% reduction in gas price, or a 100% in capital or digester costs, the scale remains viable for both gas and electricity production in both Thailand and Bangladesh.

7.6 THE VIABILITY OF WATER HYACINTH UTILISATION

As will be clear from the above discussion, the viability of water hyacinth utilisation is most evident once large-scale systems are considered. The small-scale use of the plant generates inadequate revenue to cover even the most frugal of capital and operational costs. The use of medium-scale operations may best described as borderline. Given the fact that such systems are a new proposition, without a demonstrated application existing to provide comfort for potential investors, the risk element is likely to be considered high. In the small and medium-scales there is inadequate margin between costs and revenue to make the risk acceptable.

The opportunity provided by the possibility of large-scale applications makes such schemes worthy of further investigation. As with any large-scale engineering process, this will involve investment in pilot plant trials, of a meaningful throughput, and detailed economic feasibility studies tied into specific locations. It is by the successful application of medium-scale projects that confidence will be built, through which large-scale schemes may emerge. This is one of the reasons that work to improve the viability of medium-scale schemes will assist in the development of the whole concept.

It should be noted that the loss in carbon, as measured by COD, available for conversion to biogas in the process investigated was seventy-five percent. Approximately half of the COD was lost in the process of juicing (being left in the residue mat) and the apparatus tested produced only a fifty percent conversion of the juice's COD to gas,(as measured by the COD removal efficiency parameter). It is quite clear that such losses would be devastating in the commercial operations envisaged above. At the same time, it is also realistic to consider that such losses are a matter for design optimisation. Prior art, with regard to high-rate digester designs, demonstrates that better carbon utilisation efficiencies may be achieved. The question of carbon transfer to juice is one which will require additional investigation.

Chapter 8

SUMMARY AND CONCLUSIONS

The economic potential of water hyacinth has yet to be realised on a substantial scale. This results in part from the marginal economic nature of all biogas technology and in part from the specific difficulties encountered with water hyacinth. The current research has shown that there are methods of utilising water hyacinth which hold promise for overcoming some of the principal obstacles to large scale commercial exploitation.

8.1 Choice of process

A wide range of system combinations and process options has been considered as a means to realising more than one output in a symbiotic manner from a water hyacinth feedstock. The use of "juicing", being the removal of fibrous organic constituents by mechanical means, was identified as a technology which would facilitate both the separation of useful component streams and the high-rate anaerobic digestion of the resultant dilute organic liquid.

Low-solids, high-rate digestion requires a large surface area, to enable bacteria to break down the digestible organic components rapidly. It requires a method of preventing the wash-out of slow growing methanogenic bacteria and also methods for thorough mixing to ensure good contact between bacteria and digestible organic surfaces. Without juicing, high-rate digestion, to the order of twenty-four hours, is unlikely to be achievable for water hyacinth.

Experimental work in Bangladesh and Thailand demonstrated the technical feasibility of the proposed technology. Economic analysis, by means of spreadsheets, established the necessary targets for various process efficiencies.

8.2 Experimental findings

Experimental work was undertaken in order to:

i establish technical feasibility,
ii measure key parameters required by the economic model.

There were two phases to the experimental work. In Bangladesh the research work identified the gross characteristics of water hyacinth with regard to its application in high-rate anaerobic digesters. The problems associated with the plant's buoyancy, its high lignin content and its high water content became apparent with trials on a eight cubic metre multi-stage upflow anaerobic digester in Dhaka. Associated laboratory trials indicated that a period of aerobic digestion may result in greater digestibility without a loss of methane gas product during subsequent anaerobic digestion.

In Thailand it was possible to build upon the experiences of Bangladesh and develop systems for pre-treating water hyacinth in a manner which facilitated the objective of high-rate anaerobic digestion. Batch trials demonstrated conclusively that, at least in the cases where water hyacinth is juiced before digestion, the root component should not be removed from the feedstock.

An inclined weir, multi-stage upflow anaerobic digester demonstrated an overall 50% reduction in COD with a retention time of 24 hours. COD removal rates of around 12 kg per cubic metre of digester volume per day were achieved for water hyacinth leaf. This figure compares with the best that has been achieved with any feedstock. The leaf was found to comprise around 10% of the plant's organic content, in a form which made it particularly easy to digest. With a whole-plant feedstock, COD removal rates of approximately 5.5 kg per cubic metre per day were achieved. This lower rate is a reflection of the higher refractory content of the leaf and stem. It is also a substantial improvement upon other technologies employed for the anaerobic digestion of water hyacinth. Juiced root was found to have a higher COD than juiced stem and, consequently, to produce a greater output of biogas.

The following conclusions have been drawn from the results of the experimentation:

I Separation of the fibrous fraction of water hyacinth from the feedstock by mechanical means will enable the resulting "juice" to be digested in high-rate anaerobic digesters.

II Where adequate mechanical pre-treatment is employed there is no benefit to be gained from separating the root from the leaf and stem. The root will contribute to gas production more usefully than the stem.

III The use of inclined weir plates in a multi-stage upflow anaerobic digester is a method of reducing the risk of blocking where insoluble solids are contained within a juiced feedstock.

8.2 Economic findings

An economic model was developed and built into a spreadsheet. Data was collected in Bangladesh and Thailand and input into the model, together with data derived from the experimental programme. The findings of this thesis indicate that in order to arrive at viable commercial systems, on any of the scales considered, it is necessary to make several key assumptions.

For example, it is necessary that the conversion of raw water hyacinth to juice and then to biogas, be achieved with a greater degree of efficiency than that actually obtained in the experimentation. Where the experimental conversion efficiencies are applied to the economic model, operation at all scales considered becomes non-viable. However, experimental techniques were relatively crude, being based upon readily available, locally procured equipment. A full scale commercial system can reasonably be expected to perform better, simply on the basis of process engineering design improvements.

The contribution from fertiliser and fibre to the overall system viability may not be crucial in purely economic terms. The assumptions made with regard to the value of these two outputs indicates that fibre would contribute fifteen percent of the total profit for a large-scale system. The fertiliser value, in terms of NPK, is very small but, being readily available and in a liquid form, may be immediately applied to local agricultural land. The flow rate of liquid from a median large-scale plant would be to the order of 2000 cubic metres per day. This is a nutrient rich flow which could be used with great benefit for local irrigation purposes.

One very important finding is that, regardless of how generous are the assumptions, it is not possible to create a situation where small scale utilisation of water hyacinth becomes viable. Only if the labour input were free and the capital investment could be very low would it be considered to produce a worthwhile scheme.

In a medium-scale setting (1000 m^3 biogas per day) the system proposed becomes marginally viable provided that juicing efficiencies are substantially higher than those achieved in the experimentation.

It is in large-scale applications (100,000 m^3 biogas per day) that the use of water hyacinth becomes significantly attractive. Economies of scale are such that the requirement for harvesting, for example, which can be a crucial expense in medium-scale systems, is small when compared with the system revenue. Large-scale systems are also less sensitive to comparatively large changes in other variables. This is due in part to the extended pay-back periods which can be considered for large-scale capital projects.

8.3 Outstanding issues

There, therefore, remain a number of outstanding issues which will require to be addressed prior to implementation of commercial systems.

Juicing efficiency

A number of technologies were investigated for the juicing of water hyacinth as part of the experimental programme. A principle requirement was that the method selected should be locally available in South East Asia. In practice, whilst holding much promise as a direction to be investigated further, the mincer/manual press performed with a low efficiency both in terms of energy requirement and conversion of organic content from raw feed to juice. Work is required here to improve both of these measures.

Refinement of the inclined weir reactor

Whilst demonstrating potential, the inclined weir reactor did not achieve a COD conversion to biogas at a level which would be satisfactory in a commercial setting. More work is required on the following aspects:

1. the design methodology for preventing blocking,
2. maximising biogas output by varying the geometry of the inclined weir plates and the number of riser sections.

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Appendix 1

Water hyacinth - physical properties.

WATER HYACINTH - ADDITIONAL DATA

Physical facts

The stomata of water hyacinth are similar in shape and number and distribution to those of the average mesophytic, monocotyledonous plant. The average number is 120 per mm^2 which is typical of this type of plant and the distribution is similar on both surfaces. The size of the stomatal apertures is, however, much greater than those in most plants. The average with water hyacinth is $12\ \mu \times 27\ \mu$ whereas in most plants it is about $6\ \mu \times 12\ \mu$. The inter-stomatal distances are approximately eight times the diameter of the wide open pore. From this data on stomata it is apparent that water hyacinth is well equipped for the rapid diffusion of gases.

It has been noted that the great variation in leaf size, from 30 mm x 20 mm for plants that have developed on land or in poorly oxygenated water to 135 mm x 150 mm for plants in flowing water, appears to not produce a variance in the stomata. The number per unit area and the inter stomatal distances remain the same. Moreover, the size of the stomatal pores do not vary significantly among leaves from small, medium and large plants. It may have been expected that the greatly increased size of the leaves on the large plants resulted from an augmented cell size but the above data on stomatal correlation indicates that the leaf size results from an increase in the number of cells, and not the cell size.

Established stolons are typically 10 - 25 mm in diameter but vary greatly in length. In a close stand of water hyacinth they average about 55 mm, but may grow up to 250 mm in open stands and they have on occasion been noted to reach 450 mm. At first growth the stolon points upwards at an angle of about 60° from the horizontal, and the roots point forward at the same angle (see Fig.1.1). In dense growth the stolon is so short that it maintains nearly the same position, but in open stands the stolon is soon carried to the horizontal position by the weight of the developing offshoot. The rhizomes are in general of a similar diameter to the stolons and vary in length from 100 - 300 mm.

The cone shaped rhizome crown possesses a pink cap near the periphery which is about 10 mm in length and which extends into the buds and base of the leaves. The reproductive portion of the rhizome tip varies in length from 10 mm to 40 mm in large plants. It has also been noted that the position of the tip of the rhizome varies with reference to the water surface. In small plants it may be less than 10 mm below the surface. In large plants it may however be as much as 80 mm below the surface of the water.

The roots are fibrous un-branched and with a conspicuous root cap.

They are purplish in exposed situations but white in darkness, or when rooted in the soil (Olive, 1894). They have been noted to vary little in diameter, but greatly in length from 100 mm to 1000 mm and possibly more.

Phenology

A typical growth pattern has been observed in New Orleans in the United States (Penfound, 1947). The New Orleans area has a frostless season of 322 days typically due in part to its latitude (30° North) and the warming affect in the winter of large bodies of water in the immediate facility.

In January and February the mat of water hyacinth appears completely brown, to the casual observer completely dead. By early March, however, the largest leaves will have attained an average length of approximately 100 mm and in subsequent months will grow to a maximum in August of approximately 750 mm. Maximum growth is observed from May to August at which time the leaves will have attained their maximum height. No measurable growth occurs in November or December and growth is abruptly terminated by a moderate freeze sometime in December. The moderate freeze completely destroys the leaves.

The first flowers are observed sometime in April and by early June maximum flowering has occurred. From early June to September flowering decreases and in solid mats is slight, except for the edges fronting open water. It has been noted that a definite rhythm of high and low flower production occurs in a given colony. This accounts for the observation that many flowers will be found to be blooming in one water body whilst in a similar water body in an adjacent area few or none are found to be flowering. In September and October a second period of heavy flowering commences, and this continues through November into December when freezing weather terminates all growth.

The water content of the water hyacinth plant is one that has been seen to vary depending upon the location in which the plants are obtained, and the time of year which they are obtained. One of the key elements that would affect the water content of the whole plant, is the relative proportions of the various components. It has been noted that the roots typically have a lower water content than the rhizomes and stolons. The leaf blades have the lowest moisture content, typically around 90%. The root portion of the plant may vary considerably as will the size of the leaves, and the size of the leaves and stolons. The combination of these various proportions will, therefore, determine the moisture content of the whole plant. In work carried out at Mahidol University in Thailand, it was found that, on a wet weight basis, the leaves consisted of approximately 12% of the whole plant, the stems consisted of in the region of 50% and the roots contributed a further 38%. This relationship existed because the source of the water hyacinth plant was a densely matted area of growth and consequently the stems had elongated considerably with medium sized leaves rising, typically between 300 and 600 mm in height.

A further remarkable feature with regard to water hyacinth relations with water is the rate of transpiration of the plant. It has been noted that water hyacinth may jeopardise the success of irrigation projects for two reasons. The first is that the plant will clog up the canals and various mechanisms required to operate an irrigation system successfully. The second is that the comparatively high rate of transpiration accelerates water loss. When the Aswan Dam was first opened in Egypt, there was some concern as the dam was filling that the rate of evaporation and transpiration was greater than the inflow of water into the dam. This concern has been re-experienced in different irrigation projects around the world. Work carried out on the relative rates of evaporation from a water surface and transpiration from a mat of water hyacinth in the United States, has indicated that the ratio of transpiration to evaporation, may be as high as 6.6 in clear sunny weather, with a low typically of 2. Over a full growing period the ratio was in the region of 3.6 (Penfound, 1947). The rate of transpiration is related to the total leaf surface area, and in growths of water hyacinth with small leaves, it would be expected that transpiration would be less than the maximum of 6.6. The minimum levels of transpiration were experienced when the weather conditions were cloudy or raining. In tropical conditions with high humidity it is to be expected that transpiration would therefore be less.

Another interesting relation of water hyacinth to water has been noted. In water hyacinth death usually occurs when the weight of an exposed plant falls below 15% of its initial wet weight. Such desiccation may occur when water levels in a pond, or canal, drop and leave the plant stranded on dry ground. As has been noted earlier however, in such cases the water hyacinth often roots into the banks of the water body and it continues to survive in this manner.

There are occasions when the water level of a pond or water course may rise. In the case of water hyacinth plant having become rooted, the water level will rise above the plant rhizome and submerge the bulk of the plant. The water hyacinth has two methods of responding to this situation. In the first case the plant effectively suffocates and will die. In the second case, it has been noted that the plant forms an abscission and drops the roots that are attaching it to the base of the water course and rises to the surface. This way the plant the plant can avoid suffocation.

Relationships with the environment

One key relation that affects the areas of water covered with water hyacinth is the relationship of the plant to salt. Where the water exceeds a salt concentration of 0.06% it has been found that the water hyacinth plant will die fairly rapidly. With a salt concentration of 2%, approaching that typical of sea water, a plant will die extremely rapidly by wilting and crisping and epinasty is not observed. The water hyacinth plant will grow readily in all forms of fresh water bodies. It will be found in rivers, ponds, lakes, canals, drainage ditches and all forms of irrigation systems.

One surprising aspects of its ability to grow in various locations has been noted by numerous researchers. At times during the ebb and flow of water levels water hyacinth will become stranded on dry land. In such cases it has been observed that water hyacinth will develop numerous tough roots and continue to grow with the roots penetrating into the soil. The fresh leaves will not have floats, as if the plant realises that growing on land floats are no longer necessary. Landed water hyacinth have been reported to have survived for up to five months on dry land adjacent to water courses. (Penfound, 1947)

The size of the water hyacinth can vary enormously with habitat conditions. Penfound has suggested categories of five different sizes described as midget, small, medium, large and giant. Midget plants will be found rooted on land and will have leaves typically 75 mm long. Despite their size, these midgets produce normal and apparently viable seeds. Small plants will be found along the fringes of larger plant masses and on the edge of water typically grazed by cattle. Medium sized plants will be found in water bodies with little movement, whereas large and giant plants are encountered in moving, well aerated water at the outfall of canals or in the open water of ponds. Giant plants will have leaves of up to 1,250 mm long and have been noted to rarely produce flowers or fruits. Medium sized plants will form a well developed mat with considerable raw peat, whereas large and giant plants produce poorly developed mats with very little dead material.

It has often been noted that the water hyacinth will grow with floats on the leaves in the presence of full sunlight. Floats will not be found in dense stands, under trees or when rooted on land. Elongate, equitant leaves are formed at intensities ranging from 1,400 to 5,400 lux. Float leaves are formed only when the average light intensity is above 5,400 lux. Where the average light intensity falls below 1,400 lux, it is often found that water hyacinth will be dead or dying. It is for this reason that water hyacinth do not survive well in laboratories where the average light intensity will be approximately 200 lux.

Appendix 2

Tabulated results from batch trials in Thailand.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

MEASURED PARAMETER

Daily gas production (ml)
Daily gas production less seed gas (ml)
Juice gas production rate (l/kg dry wt/day)
Juice gas production rate (l/l/day)
Juice gas production rate (l/kg VS/day)
Juice gas production rate (l/kg COD/day)
Total juice + seed gas produced (ml)
Total juice gas produced (ml)
Total juice gas produced (l)
Total juice gas produced (l/l)
Total juice gas (l/kg VS)
Total juice gas (l/kg COD)
Total juice gas (l/kg dry wt)

STEM JUICE 1

MEASURED PARAMETER

Daily gas production (ml)
Daily gas production less seed gas (ml)
Juice gas production rate (l/kg dry wt/day)
Juice gas production rate (l/l/day)
Juice gas production rate (l/kg VS/day)
Juice gas production rate (l/kg COD/day)
Total juice + seed gas produced (ml)
Total juice gas produced (ml)
Total juice gas produced (l)
Total juice gas produced (l/l)
Total juice gas (l/kg VS)
Total juice gas (l/kg COD)
Total juice gas (l/kg dry wt)

STEM JUICE 2

MEASURED PARAMETER

Daily gas production (ml)
Daily gas production less seed gas (ml)
Juice gas production rate (l/kg dry wt/day)
Juice gas production rate (l/l/day)
Juice gas production rate (l/kg VS/day)
Juice gas production rate (l/kg COD/day)
Total juice + seed gas produced (ml)
Total juice gas produced (ml)
Total juice gas produced (l)
Total juice gas produced (l/l)
Total juice gas (l/kg VS)
Total juice gas (l/kg COD)
Total juice gas (l/kg dry wt)

STEM JUICE 3

MEASURED PARAMETER

Daily gas production (ml)
Daily gas production less seed gas (ml)
Juice gas production rate (l/kg dry wt/day)
Juice gas production rate (l/l/day)
Juice gas production rate (l/kg VS/day)
Juice gas production rate (l/kg COD/day)
Total juice + seed gas produced (ml)
Total juice gas produced (ml)
Total juice gas produced (l)
Total juice gas produced (l/l)
Total juice gas (l/kg VS)
Total juice gas (l/kg COD)
Total juice gas (l/kg dry wt)

STEM JUICE 4

Date started: 24/12/92
COD pulp = 6,460 mg/l
VS pulp = 8,700 mg/l
COD Seed No.3 = 3,456 mg/l
Vol juice = 2,100 ml
Vol seed = 1,200 ml
Dry wt = 14,126 mg/l

MEASURED PARAMETER

Daily gas production (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Daily gas production less seed gas (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg dry wt/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/l/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg VS/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg COD/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice+seed gas produced (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced(ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l/l)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg VS)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg COD)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg dry wt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

STEM PULP 5

Date started: 3/12/92
COD pulp = 61,450 mg/l
VS pulp = 46,950 mg/l
COD Seed No.4 = 7,780 mg/l
Vol juice = 2,380 ml
Vol seed = 320 ml
Dry wt = 60,910 mg/l

MEASURED PARAMETER

Daily gas production (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Daily gas production less seed gas (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg dry wt/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/l/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg VS/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg COD/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice+seed gas produced (ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced(ml)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l/l)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg VS)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg COD)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg dry wt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LEAF JUICE 1

Date started: 3/12/92
COD pulp = 21,435 mg/l
VS pulp = 18,750 mg/l
COD Seed No.1 = 2,050 mg/l
Vol juice = 1,850 ml
Vol seed = 1,300 ml
Dry wt = 18,750 mg/l

MEASURED PARAMETER

Daily gas production (ml)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Daily gas production less seed gas (ml)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg dry wt/day)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/l/day)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg VS/day)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg COD/day)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice+seed gas produced (ml)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced(ml)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l/l)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg VS)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg COD)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg dry wt)	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LEAF JUICE 2

Date started: 3/12/92
COD pulp = 24,300 mg/l
VS pulp = 22,730 mg/l
COD Seed No.2 = 5,435 mg/l
Vol juice = 2,640 ml
Vol seed = 660 ml
Dry wt = 22,730 mg/l

MEASURED PARAMETER

Daily gas production (ml)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15	20 Converted into Leaf [illegible]
Daily gas production less seed gas (ml)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15	20
Juice gas production rate (l/kg dry wt/day)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/l/day)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg VS/day)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Juice gas production rate (l/kg COD/day)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice+seed gas produced (ml)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced(ml)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas produced (l/l)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg VS)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg COD)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total juice gas (l/kg dry wt)	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LEAF JUICE 3

Date started: [illegible]
COD pulp = [illegible] mg/l
VS pulp = [illegible] mg/l
COD Seed No 3 = [illegible] mg/l
Vol juice = 2,100 ml
Vol seed = 1,200 ml
Dry wt = [illegible] mg/l

MEASURED PARAMETER

MEASURED PARAMETER	
Daily gas production (ml)	[illegible]
Daily gas production less seed gas (ml)	[illegible]
Juice gas production rate (l/kg dry wt/day)	[illegible]
Juice gas production rate (l/l/day)	[illegible]
Juice gas production rate (l/kg VS/day)	[illegible]
Juice gas production rate (l/kg COD/day)	[illegible]
Total juice+seed gas produced (ml)	[illegible]
Total juice gas produced (ml)	[illegible]
Total juice gas produced (l)	[illegible]
Total juice gas produced (l/l)	[illegible]
Total juice gas (l/kg VS)	[illegible]
Total juice gas (l/kg COD)	[illegible]
Total juice gas (l/kg dry wt)	[illegible]

LEAF PULP 4

Date started: [illegible]
COD pulp = [illegible] mg/l
VS pulp = [illegible] mg/l
COD Seed No 4 = [illegible] mg/l
Vol juice = 2,500 ml
Vol seed = 700 ml
Dry wt = [illegible] mg/l

MEASURED PARAMETER	
Daily gas production (ml)	[illegible]
Daily gas production less seed gas (ml)	[illegible]
Juice gas production rate (l/kg dry wt/day)	[illegible]
Juice gas production rate (l/l/day)	[illegible]
Juice gas production rate (l/kg VS/day)	[illegible]
Juice gas production rate (l/kg COD/day)	[illegible]
Total juice+seed gas produced (ml)	[illegible]
Total juice gas produced (ml)	[illegible]
Total juice gas produced (l)	[illegible]
Total juice gas produced (l/l)	[illegible]
Total juice gas (l/kg VS)	[illegible]
Total juice gas (l/kg COD)	[illegible]
Total juice gas (l/kg dry wt)	[illegible]

WHOLE PLANT JUICE 1

Date started: [illegible]
COD pulp = [illegible] mg/l
VS pulp = [illegible] mg/l
COD Seed No 4 = [illegible] mg/l
Vol juice = [illegible] ml
Vol seed = [illegible] ml
Dry wt = [illegible] mg/l

MEASURED PARAMETER	
Daily gas production (ml)	[illegible]
Daily gas production less seed gas (ml)	[illegible]
Juice gas production rate (l/kg dry wt/day)	[illegible]
Juice gas production rate (l/l/day)	[illegible]
Juice gas production rate (l/kg VS/day)	[illegible]
Juice gas production rate (l/kg COD/day)	[illegible]
Total juice+seed gas produced (ml)	[illegible]
Total juice gas produced (ml)	[illegible]
Total juice gas produced (l)	[illegible]
Total juice gas produced (l/l)	[illegible]
Total juice gas (l/kg VS)	[illegible]
Total juice gas (l/kg COD)	[illegible]
Total juice gas (l/kg dry wt)	[illegible]

SEED JUICE 1

Daily gas production (ml)	[illegible]
Production rate (l/l/day)	[illegible]
Total	[illegible]

15 Ceased [illegible]

SEED JUICE 2

Daily gas production (ml)	[illegible]
Production rate (l/l/day)	[illegible]
Total	[illegible]

Converted into Seed 3 [illegible]

SEED JUICE 3

Daily gas production (ml)	[illegible]
Production rate (l/l/day)	[illegible]
Total	[illegible]

SEED JUICE 4

Daily gas production (ml)	[illegible]
Production rate (l/l/day)	[illegible]
Total	[illegible]

Appendix 3

Tabulated results from high-rate digestion trials in Thailand.

*** RUN NUMBER 1 ***

ENERGY FROM BIOMASS VIA METHANE
Results obtained from an IWR in Bangkok, 1992
Liquid volume of digester = 5 litres
Gas volume of digester = 0.162 litres

MONITORED PARAMETERS

Day from start	0	1	2	3	4
Root juice only	Mon	Tues	Wed	Thur	Fri
Sart date: 7/12/92	7/12/92	8/12/92	9/12/92	10/12/92	11/12/92
Ambient temperature (Deg C)	28	33	32	32	31
Process temperature (Deg C)	26	30	29	28	27
CH4 (%)		8	15.5	24	32
CO2 (%)		9.5	25	35	46
Volume of biogas produced per day (ml)		131	437	3040	4460
Estimated gas production (ml)					
Actual with estimate gas production (ml)		131	437	3040	4460
Influent volatile Solids (Measures values)(mg/l)	11526	11435			12538
Influent volatile Solids (Calculated values)(mg/l)	11526	11222	11722	12461	12490
Effluent volatile solids (Measured values)(mg/l)		11112			
Effluent volatile solids (Calculated values)(mg/l)		11112	9690	8816	7341
Influent total Solids (mg/l)			19587		
Effluent total solids (mg/l)			16006		
INPUT COD (mg/l)	13250	12900	13475	14325	14358
Estimated values (mg/l)					
Actuals with estimates (mg/l)	13250	12900	13475	14325	14358
OUTPUT COD (mg/l)		12450	10857	9877	8225
Estimated values (mg/l)					
Actuals with estimates (mg/l)		12450	10857	9877	8225
Actual influent flow rate (ml/hr)	51	52	55	145	136
Estimate influent flow rate (ml/hr)					
Actual with estimate influent flow rate (ml/hr)	51	52	55	145	136

CALCULATED VALUES

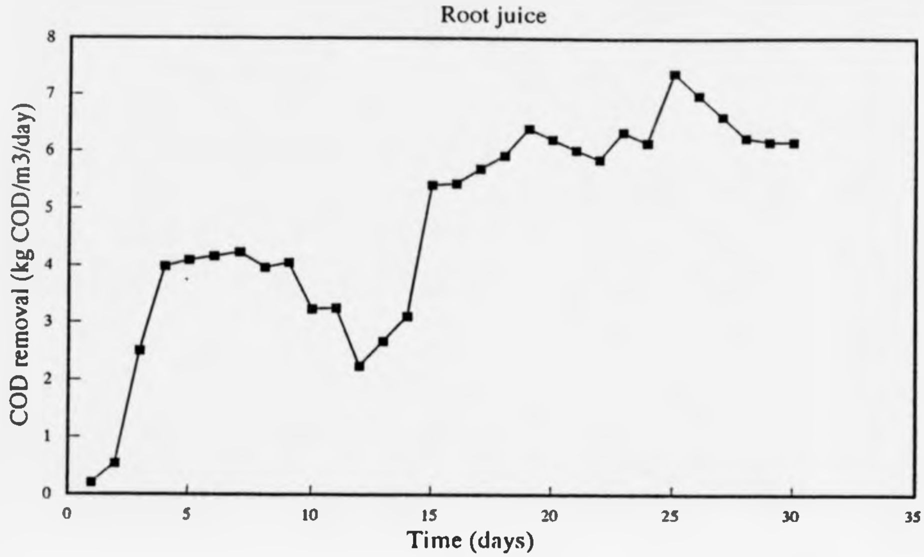
Gas production (l/l digester vol/day)	0.00	0.03	0.09	0.61	0.89
Gas production (l/kg VS/day)	0.0	9.3	31.2	196.5	102.8
Gas production (l/kg COD/day)	0.0	8.1	27.1	170.9	89.5
Hydraulic retention time (hrs)	98	96	91	34	37
Hydraulic retention time (days)	4.08	4.01	3.79	1.44	1.53
Hydraulic velocity in base of riser (m/hr)	0.16	0.17	0.18	0.46	0.44
Hydraulic velocity at overflow from riser (m/hr)	0.008	0.008	0.008	0.022	0.021
Organic loading (kg COD/m3/day)	3.2	3.2	3.6	10.0	9.4
Organic loading (kg VS/m3/day)	2.8	2.8	3.1	8.7	8.2
COD removal efficiency (%)		6.0	15.8	26.7	42.6
COD removal (kg COD/m3 day)		0.2	0.5	2.5	4.0

5	6	7	8	9	10	11	12	13	14
Sat	Sun	Mon	Tues	Wed	Thur	Fri	Sat	Sun	Mon
12/12/92	13/12/92	14/12/92	15/12/92	16/12/92	17/12/92	18/12/92	19/12/92	20/12/92	21/12/92
30	29	33	33	22	25	30	31	30	32
		29	28	24	21	26			28
		51	54	45	48	43			53
		49	45	47	52	54			46
		5562	4600	5354	4740	4154			7978
4827	5195						5429	6703	
4827	5195	5562	4600	5354	4740	4154	5429	6703	7978
12490	12490	12124	11677	12089	12662	11344	11344	11344	13453
7463	7584	7706	7528	8399	9469	9863	9561	9258	8955
		13937	13423	13897	14556	13041			15465
14358	14358						13041	13041	
14358	14358	13937	13423	13897	14556	13041	13041	13041	15465
		8634	8434	9410	10609	11051			10033
8361	8498						10712	10372	
8361	8498	8634	8434	9410	10609	11051	10712	10372	10033
		154	150	210	205	193			215
142	148						200	208	
142	148	154	150	210	205	193	200	208	215
0.97	1.04	1.11	0.92	1.07	0.95	0.83	1.09	1.34	1.60
118.4	122.0	125.4	102.7	127.4	77.8	66.7	103.3	123.1	140.9
103.0	106.2	109.1	89.3	110.8	67.7	58.0	89.9	107.1	122.5
35	34	32	33	24	24	26	25	24	23
1.47	1.41	1.35	1.39	0.99	1.02	1.08	1.04	1.00	0.97
0.46	0.47	0.49	0.48	0.67	0.66	0.62	0.64	0.67	0.69
0.021	0.022	0.023	0.023	0.032	0.031	0.029	0.030	0.031	0.032
9.8	10.2	10.3	9.7	14.0	14.3	12.1	12.5	13.0	16.0
8.5	8.9	9.0	8.4	12.2	12.5	10.5	10.9	11.3	13.9
41.8	40.8	39.9	39.5	29.9	23.7	24.1	17.9	20.5	23.1
4.1	4.2	4.2	4.0	4.0	3.2	3.2	2.2	2.7	3.1

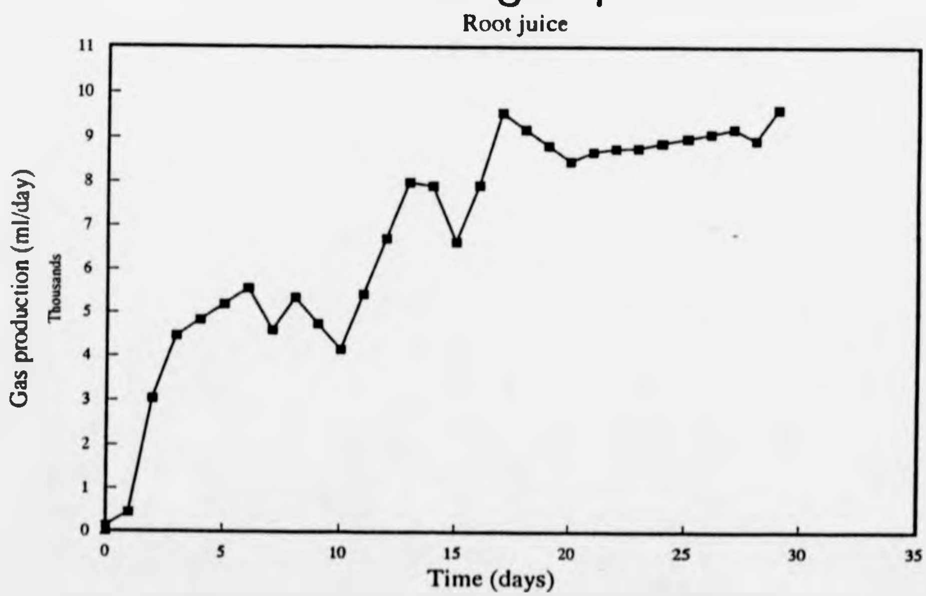
15	16	17	18	19	20	21	22	23	24
Tues	Wed	Thur	Fri	Sat	Sun	Mon	Tues	Wed	Thur
22/12/92	23/12/92	24/12/92	25/12/92	26/12/92	27/12/92	28/12/92	29/12/92	30/12/92	31/12/92
31	30	29	30	28	29	31	31	33	30
27	28	28	29			28	29	30	29
55	53	52	54			46	56	53	51
42	46	48	45			49	43	45	47
7901	6630	7920	9545			8460	8670	8748	8761
				9183	8822				
7901	6630	7920	9545	9183	8822	8460	8670	8748	8761
12696	13229	12488	13031	13031	13031	12696	12462	11973	13346
9227	8144	8226	7661	7569	7477	7385	7413	7831	6967
14595	15207	14356	14980			14595	14326	13764	15342
				14980	14980				
14595	15207	14356	14980	14980	14980	14595	14326	13764	15342
10338	9125	9216	8583			8274	8306	8774	7806
				8480	8377				
10338	9125	9216	8583	8480	8377	8274	8306	8774	7806
220	207	198	214			187	194	238	215
				205	196				
220	207	198	214	205	196	187	194	238	215
1.58	1.33	1.58	1.91	1.84	1.76	1.69	1.73	1.75	1.75
113.8	98.9	120.5	160.8	137.2	137.6	138.0	152.2	150.8	128.1
99.0	86.0	104.8	139.9	119.4	119.7	120.1	132.4	131.2	111.4
23	24	25	23	24	26	27	26	21	23
0.95	1.01	1.05	0.97	1.02	1.06	1.11	1.07	0.88	0.97
0.71	0.66	0.63	0.69	0.66	0.63	0.60	0.62	0.76	0.69
0.033	0.031	0.030	0.032	0.031	0.030	0.028	0.029	0.036	0.032
15.4	15.1	13.6	15.4	14.7	14.1	13.1	13.3	15.7	15.8
13.4	13.1	11.9	13.4	12.8	12.3	11.4	11.6	13.7	13.8
33.2	37.5	39.4	40.2	43.4	44.1	44.8	43.1	38.8	43.3
5.4	5.4	5.7	5.9	6.4	6.2	6.0	5.9	6.3	6.1

25	26	27	28	29	30
Fri	Sat	Sun	Mon	Tues	Wed
1/1/93	2/1/93	3/1/93	4/1/93	5/1/93	6/1/93
31	34	28	27	29	30
			24	26	28
			51	54	55
			47	44	44
			9195	8944	9622
8870	8978	9087			
8870	8978	9087	9195	8944	9622
13346	13346	13346	12833	13425	11608
7030	7092	7155	7217	7905	7893
			14752	15433	13344
15342	15342	15342			
15342	15342	15342	14752	15433	13344
			8086	8857	8843
7876	7946	8016			
7876	7946	8016	8086	8857	8843
			179	218	195
206	197	188			
206	197	188	179	218	195
1.77	1.80	1.82	1.84	1.79	1.92
128.8	136.1	144.0	152.7	162.2	137.0
112.0	118.4	125.3	132.8	141.1	119.2
24	25	27	28	23	26
1.01	1.06	1.11	1.16	0.96	1.07
0.66	0.63	0.60	0.57	0.70	0.63
0.031	0.030	0.028	0.027	0.033	0.029
15.2	14.5	13.8	12.7	16.1	12.5
13.2	12.6	12.0	11.0	14.0	10.9
48.7	48.2	47.8	47.3	40.0	42.7
7.4	7.0	6.6	6.2	6.2	6.2

IWR - COD removal rates

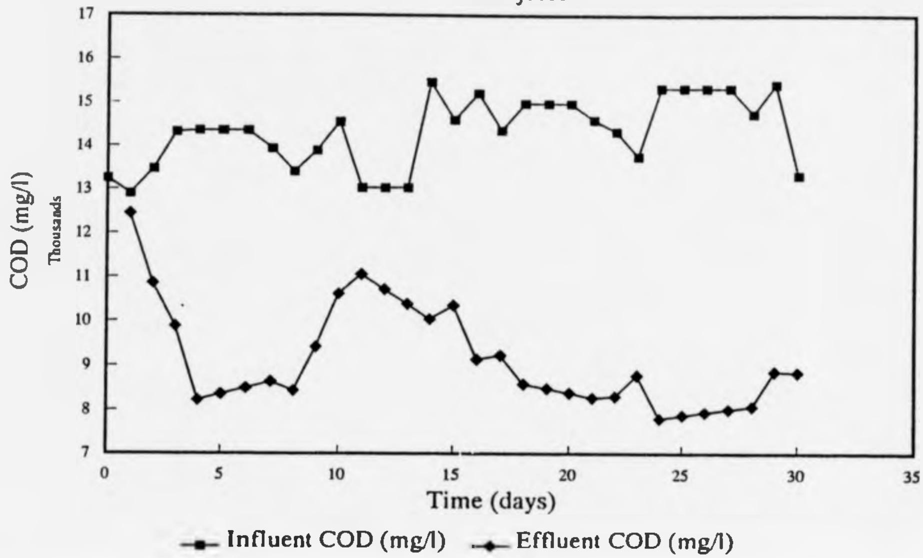


IWR - Actual gas production



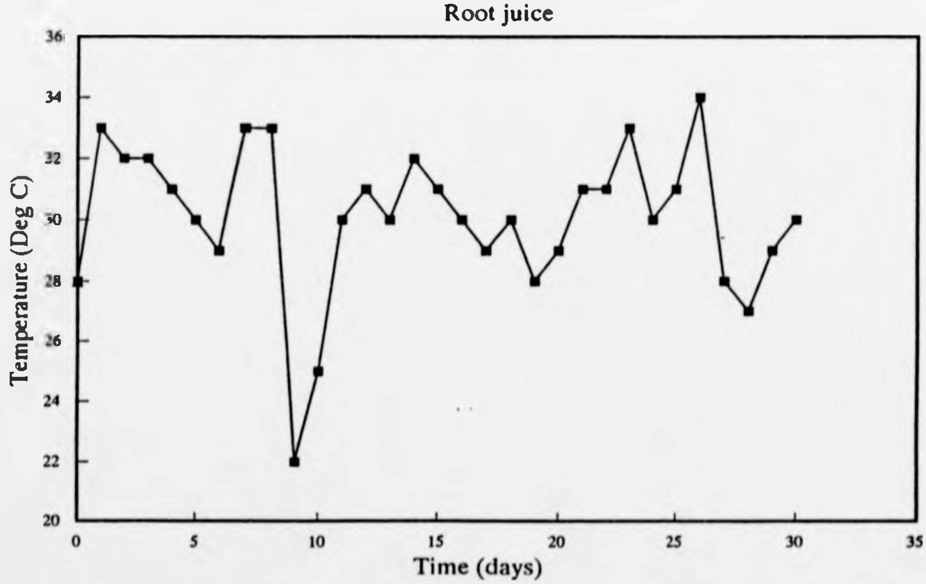
IWR -Influent vs Effluent COD

Root juice



IWR trials - temperature profile

Root juice



*** RUN NUMBER 2 ***

ENERGY FROM BIOMASS VIA METHANE
Results obtained from an IWR in Bangkok, 1992
Liquid volume of digester = 5 litres
Gas volume of digester = 0.162 litres

MONITORED PARAMETERS

Day from start	0	1	2	3	4
Stem juice only	Wed	Thur	Fri	Sat	Sun
Sart date: 2/12/92	2/12/92	3/12/92	4/12/92	5/12/92	6/12/92
Ambient temperature (Deg C)	33	32	34	31	32
Process temperature (Deg C)		28	31		
CH4 (%)		3	6.5		
CO2 (%)		9.5	17		
Volume of biogas produced per day (ml)		192	243		
Estimated gas production (ml)				896	1548
Actual with estimate gas production (ml)		192	243	896	1548
Influent volatile Solids (Measures values)(mg/l)	6024	7044			
Influent volatile Solids (Calculated values)(mg/l)	6024	6359	5953	5953	5953
Effluent volatile solids (Measured values)(mg/l)		3658			
Effluent volatile solids (Calculated values)(mg/l)		5013	5107	4548	3988
Influent total Solids (mg/l)		21348			
Effluent total solids (mg/l)		17226			
INPUT COD (mg/l)	8850	9342	8745		
Estimated values (mg/l)				8745	8745
Actuals with estimates (mg/l)	8850	9342	8745	8745	8745
OUTPUT COD (mg/l)		7441	7580		
Estimated values (mg/l)				6750	5920
Actuals with estimates (mg/l)		7441	7580	6750	5920
Actual influent flow rate (ml/hr)	53	51	48		
Estimate influent flow rate (ml/hr)				150	150
Influent flow rate (ml/hr)	53	51	48	150	150

CALCULATED VALUES

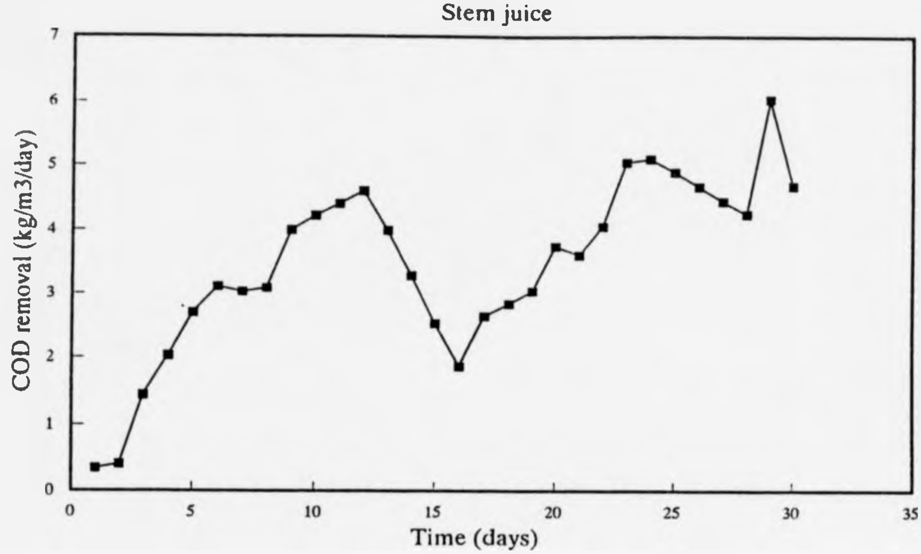
Gas production (l/l digester vol/day)		0.04	0.05	0.18	0.31
Gas production (l/kg VS/day)		25.06	31.22	130.61	72.25
Gas production (l/kg COD/day)		17.06	21.25	88.91	49.18
Hydraulic retention time (hrs)	94	98	104	33	33
Hydraulic retention time (days)	3.93	4.08	4.34	1.39	1.39
Hydraulic velocity in base of riser (m/hr)	0.17	0.16	0.15	0.48	0.48
Hydraulic velocity at overflow from riser (m/hr)	0.0080	0.0077	0.0072	0.0226	0.0226
Organic loading (kg COD/m3/day)	2.3	2.3	2.0	6.3	6.3
Organic loading (kg VS/m3/day)	1.5	1.6	1.4	4.3	4.3
COD removal efficiency (%)		15.9	18.9	22.8	32.3
COD removal (kg COD/m3 day)		0.3	0.4	1.4	2.0

5	6	7	8	9	10	11	12	13	14
Mon	Tues	Wed	Thur	Fri	Sat	Sun	Mon	Tues	Wed
7/12/92	8/12/92	9/12/92	10/12/92	11/12/92	12/12/92	13/12/92	14/12/92	15/12/92	16/12/92
28	33	32	32	31	30	29	33	33	22
26	30	29	28	27			29	28	24
26	42	32	51	41			53	44	55
38	47	52	41	48			45	56	43
2201	2835	2799	3290	4159			4925	4827	3845
					4414	4670			
2201	2835	2799	3290	4159	4414	4670	4925	4827	3845
6645	6434	5982	6434	6447	6447	6447	6044	6634	5582
3674									
3429	3626	3435	3106	3707	3558	3409	3260	3094	4440
9763	9453	8789	9453	9471			8879	9746	8201
					9471	9471			
9763	9453	8789	9453	9471	9471	9471	8879	9746	8201
5090	5383	5098	4611	5502			4839	4592	6591
					5281	5060			
5090	5383	5098	4611	5502	5281	5060	4839	4592	6591
154	148	145	154	211			207	194	217
					210	208			
154	148	145	154	211	210	208	207	194	217
0.44	0.57	0.56	0.66	0.83	0.88	0.93	0.99	0.97	0.77
102.71	115.42	122.47	158.03	174.88	135.22	143.72	153.04	160.76	124.48
69.91	78.57	83.36	107.57	119.04	92.04	97.83	104.17	109.43	84.73
32	34	34	32	24	24	24	24	26	23
1.35	1.41	1.44	1.35	0.99	0.99	1.00	1.01	1.07	0.96
0.49	0.47	0.46	0.49	0.68	0.67	0.67	0.66	0.62	0.70
0.0232	0.0223	0.0219	0.0232	0.0318	0.0317	0.0314	0.0312	0.0293	0.0327
7.2	6.7	6.1	7.0	9.6	9.5	9.5	8.8	9.1	8.5
4.9	4.6	4.2	4.8	6.5	6.5	6.4	6.0	6.2	5.8
41.8	44.9	46.1	47.5	41.8	44.2	46.6	48.9	48.3	32.4
2.7	3.1	3.0	3.1	4.0	4.2	4.4	4.6	4.0	3.3

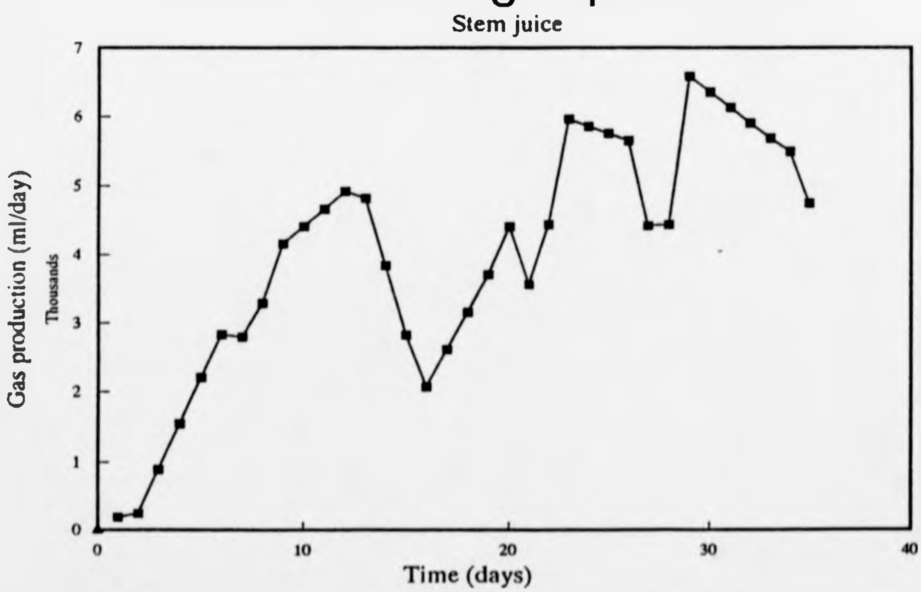
15	16	17	18	19	20	21	22	23	24
Thur	Fri	Sat	Sun	Mon	Tues	Wed	Thur	Fri	Sat
17/12/92	18/12/92	19/12/92	20/12/92	21/12/92	22/12/92	23/12/92	24/12/92	25/12/92	26/12/92
25	30	.31	30	32	31	30	29	30	28
21	26			28	27	28	28	29	
53	51			51	55	48	57	54	
46	47			47	43	49	41	46	
2823	2071			3706	4416	3567	4444	5962	
		2616	3161						5860
2823	2071	2616	3161	3706	4416	3567	4444	5962	5860
5443	5894	5894	5894	6359	6440	5840	6136	6314	6314
3968	3964	3851	3738	3625	3885	3710	2917	2907	3009
7997	8659			9342	9461	8579	9015	9276	
		8659	8659						9276
7997	8659	8659	8659	9342	9461	8579	9015	9276	9276
5890	5884			5381	5767	5507	4330	4315	
		5716	5549						4466
5890	5884	5716	5549	5381	5767	5507	4330	4315	4466
228	184			193	218	190	199	224	
		187	190						221
228	184	187	190	193	218	190	199	224	221
0.56	0.41	0.52	0.63	0.74	0.88	0.71	0.89	1.19	1.17
97.10	69.53	100.51	119.50	137.89	149.93	105.87	166.89	203.43	172.63
66.10	47.33	68.41	81.34	93.86	102.05	72.06	113.60	138.47	117.50
22	27	27	26	26	23	26	25	22	23
0.91	1.13	1.11	1.10	1.08	0.96	1.10	1.05	0.93	0.94
0.73	0.59	0.60	0.61	0.62	0.70	0.61	0.64	0.72	0.71
0.0344	0.0278	0.0282	0.0287	0.0291	0.0329	0.0287	0.0300	0.0338	0.0333
8.8	7.6	7.8	7.9	8.7	9.9	7.8	8.6	10.0	9.8
6.0	5.2	5.3	5.4	5.9	6.7	5.3	5.9	6.8	6.7
28.2	26.4	34.0	35.9	37.9	38.3	41.8	49.5	52.1	51.9
2.5	1.9	2.6	2.8	3.0	3.7	3.6	4.1	5.1	5.1

25	26	27	28	29	30
Sun	Mon	Tues	Wed	Thur	Fri
27/12/92	28/12/92	29/12/92	30/12/92	31/12/92	1/1/93
29	31	31	33	30	31
	28	29	30	29	
	50	48	52	53	
	46	50	46	46	
	5655	4429	4447	6585	
5757					6360
5757	5655	4429	4447	6585	6360
6314	5960	6360	7383	6490	6490
3111	3212	2938	3048	3363	3323
	8756	9343	10847	9534	
9276					9534
9276	8756	9343	10847	9534	9534
	4768	4361	4524	4992	
4617					4933
4617	4768	4361	4524	4992	4933
	216	211	184	215	
219					212
219	216	211	184	215	212
1.15	1.13	0.89	0.89	1.32	1.27
171.92	170.40	143.35	138.08	201.96	189.94
117.02	115.99	97.57	93.99	137.47	129.29
23	23	24	27	23	24
0.95	0.96	0.99	1.13	0.97	0.98
0.70	0.69	0.68	0.59	0.69	0.68
0.0330	0.0326	0.0318	0.0278	0.0324	0.0320
9.8	9.1	9.5	9.6	9.8	9.7
6.6	6.2	6.4	6.5	6.7	6.6
50.2	48.6	50.2	51.6	54.0	48.3
4.9	4.7	4.5	4.3	6.0	4.7

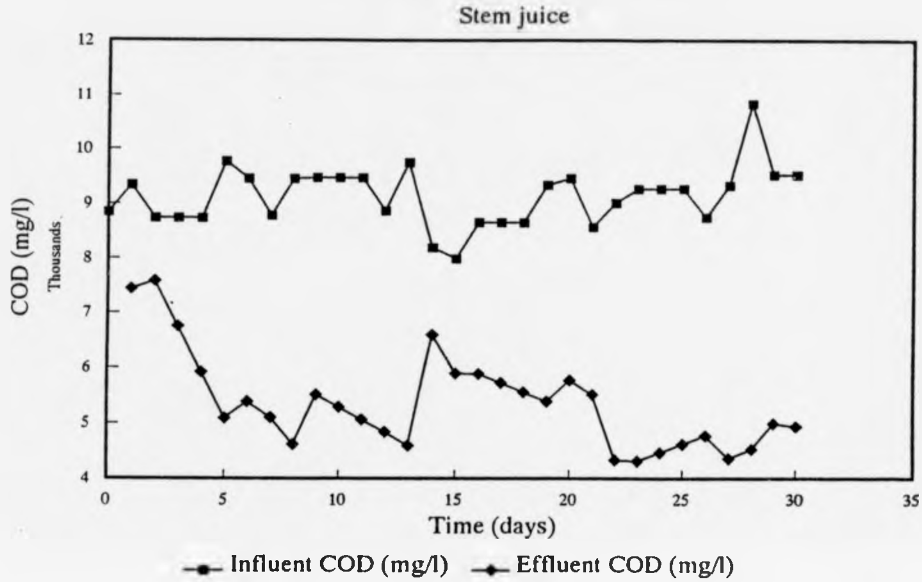
IWR - COD removal rates



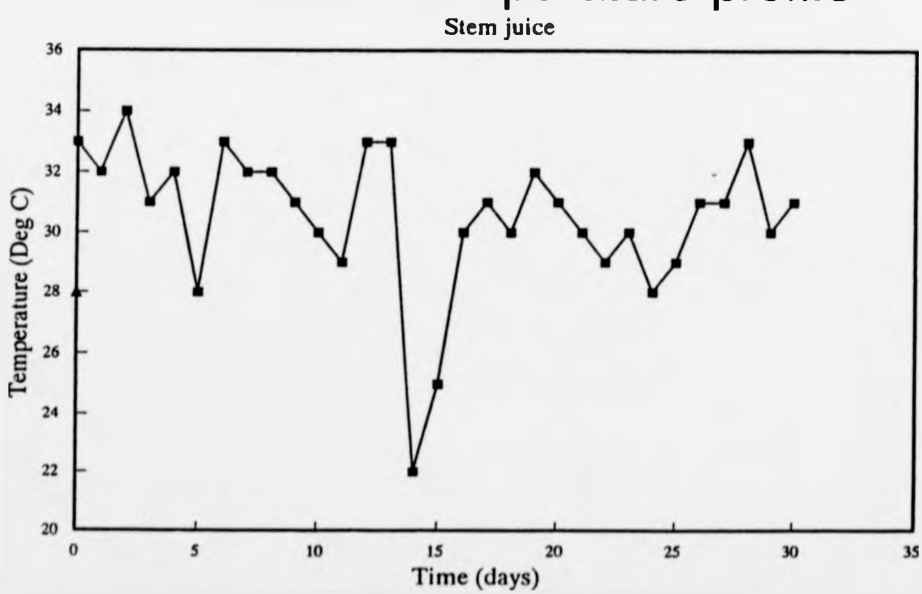
IWR - Actual gas production



IWR -Influent vs Effluent COD



IWR trials - temperature profile



*** RUN NUMBER 3 ***

ENERGY FROM BIOMASS VIA METHANE
Results obtained from an IWR in Bangkok, 1992
Liquid volume of digester = 5 litres
Gas volume of digester = 0.162 litres

MONITORED PARAMETERS

Day from start	0	1	2	3	4
Leaf juice only	Wed	Thur	Fri	Sat	Sun
Sart date: 9/12/92	9/12/92	10/12/92	11/12/92	12/12/92	13/12/92
Ambient temperature (Deg C)	32	32	31	30	29
CH4 (%)		6.7	10		
CO2 (%)		12	19		
Volume of biogas produced per day (ml)		1041	1284		
Estimated gas production (ml)				3370	5455
Actual with estimate gas production (ml)		1041	1284	3370	5455
Influent volatile Solids (Measures values)(mg/l)	18472				
Influent volatile Solids (Calculated values)(mg/l)	18472	18748	23670	23670	23670
Effluent volatile solids (Measured values)(mg/l)		15315			
Effluent volatile solids (Calculated values)(mg/l)		15315	15545	16513	17482
Influent total Solids (mg/l)			33113		
Effluent total solids (mg/l)			19458		
INPUT COD (mg/l)	19846	20143	25431		
Estimated values (mg/l)				25431	25431
Actuals with estimates (mg/l)	19846	20143	25431	25431	25431
OUTPUT COD (mg/l)		16372	16617		
Estimated values (mg/l)				17653	18688
Actuals with estimates (mg/l)		16372	16617	17653	18688
Actual influent flow rate (ml/hr)	49	54	52		
Estimate influent flow rate (ml/hr)				150	150
Influent flow rate (ml/hr)	49	54	52	150	150

CALCULATED VALUES

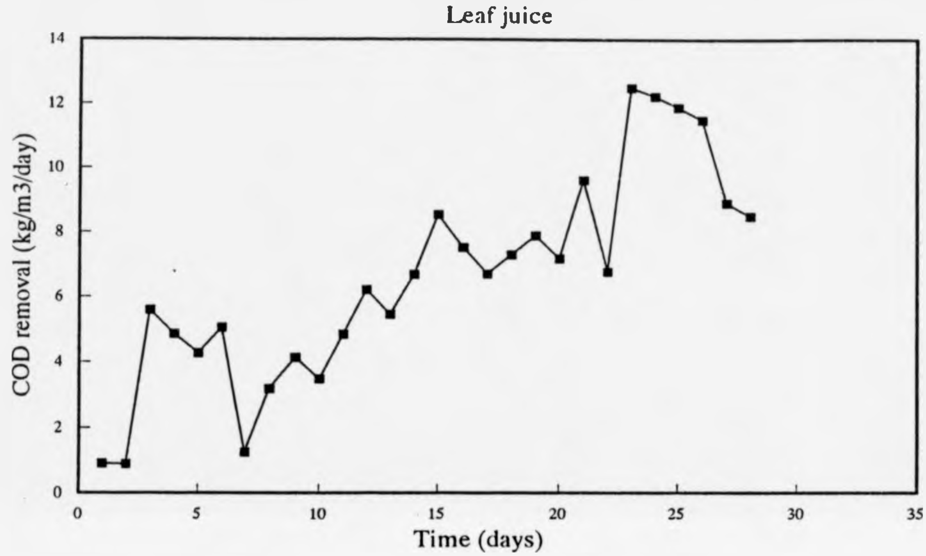
Gas production (l/l digester vol/day)	0.00	0.21	0.26	0.67	1.09
Gas production (l/kg VS/day)	0.00	47.92	52.85	114.07	64.02
Gas production (l/kg COD/day)	0.00	44.60	49.19	106.17	59.59
Hydraulic retention time (hrs)	102	93	96	33	33
Hydraulic retention time (days)	4.25	3.86	4.01	1.39	1.39
Hydraulic velocity in base of riser (m/hr)	0.16	0.17	0.17	0.48	0.48
Hydraulic velocity at overflow from riser (m/hr)	0.0074	0.0081	0.0078	0.0226	0.0226
Organic loading (kg COD/m3/day)	4.7	5.2	6.3	18.3	18.3
Organic loading (kg VS/m3/day)	4.3	4.9	5.9	17.0	17.0
COD removal efficiency (%)		17.5	17.5	30.6	26.5
COD removal (kg COD/m3 day)		0.9	0.9	5.6	4.9

5	6	7	8	9	10	11	12	13	14
Mon	Tues	Wed	Thur	Fri	Sat	Sun	Mon	Tues	Wed
14/12/92	15/12/92	16/12/92	17/12/92	18/12/92	19/12/92	20/12/92	21/12/92	22/12/92	23/12/92
33	33	22	25	30	31	30	32	31	30
26	42	32	51	41			53	44	55
38	47	52	41	48			45	56	43
7541	9397	1952	5187	6957			10986	9879	11509
					8300	9643			
7541	9397	1952	5187	6957	8300	9643	10986	9879	11509
25915	22966	22667	26809	25044	25044	25044	21811	20793	22667
18451	19351	21460	18794	23189	22034	20878	19722	16291	14568
27843	24675	24354	28804	26908			23434	22340	24354
					26908	26908			
27843	24675	24354	28804	26908	26908	26908	23434	22340	24354
19724	20687	22941	20091	24790			21083	17415	15573
					23554	22319			
19724	20687	22941	20091	24790	23554	22319	21083	17415	15573
156	147	149	156	215			222	189	206
					217	220			
156	147	149	156	215	217	220	222	189	206
1.51	1.88	0.39	1.04	1.39	1.66	1.93	2.20	1.98	2.30
88.50	96.85	24.09	63.99	69.31	64.23	73.82	83.21	85.01	122.03
82.37	90.14	22.42	59.56	64.51	59.78	68.71	77.44	79.12	113.57
32	34	34	32	23	23	23	23	26	24
1.34	1.42	1.40	1.34	0.97	0.96	0.95	0.94	1.10	1.01
0.50	0.47	0.48	0.50	0.69	0.70	0.70	0.71	0.61	0.66
0.0235	0.0222	0.0225	0.0235	0.0324	0.0328	0.0331	0.0335	0.0285	0.0311
20.8	17.4	17.4	21.6	27.8	28.1	28.4	25.0	20.3	24.1
19.4	16.2	16.2	20.1	25.8	26.1	26.4	23.2	18.9	22.4
22.4	25.7	7.0	17.5	13.9	12.5	17.1	21.6	25.7	30.3
4.3	5.0	1.2	3.2	4.1	3.5	4.8	6.2	5.5	6.7

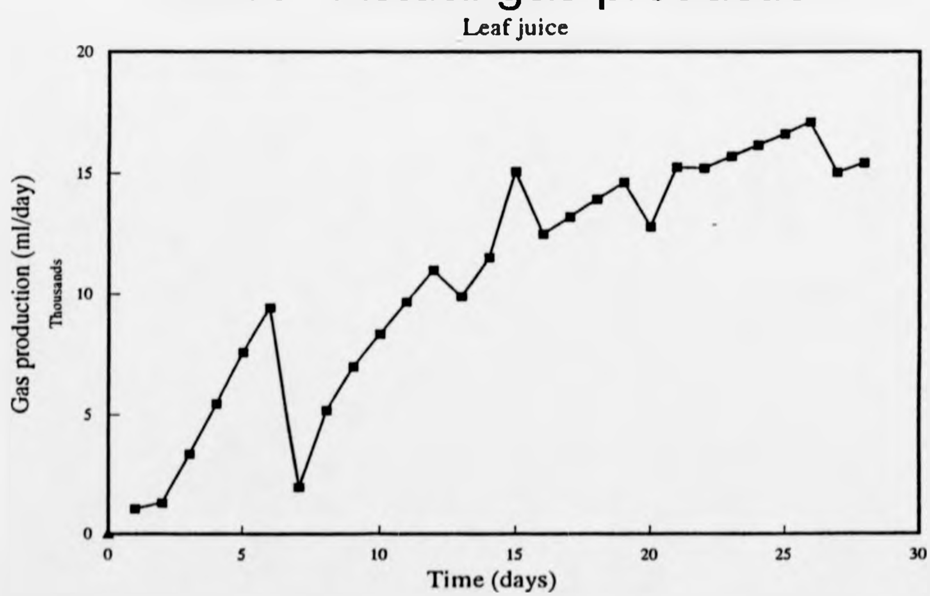
15	16	17	18	19	20	21	22	23	24
Thur	Fri	Sat	Sun	Mon	Tues	Wed	Thur	Fri	Sat
24/12/92	25/12/92	26/12/92	27/12/92	28/12/92	29/12/92	30/12/92	31/12/92	1/1/93	2/1/93
29	30	28	29	31	31	33	30	31	34
53	51			52	55	48	57		
46	47			46	43	49	41		
15057	12483			14609	12775	15238	15204		
		13192	13900					15677	16150
15057	12483	13192	13900	14609	12775	15238	15204	15677	16150
22679	21373	21373	21373	18498	26928	19845	25935	25935	25935
15589	15779	15221	14662	14104	12118	17768	12962	13674	14385
24366	22963			19874	28932	21322	27865		
		22963	22963					27865	27865
24366	22963	22963	22963	19874	28932	21322	27865	27865	27865
16665	16868			15077	12954	18994	13857		
		16271	15674					14617	15378
16665	16868	16271	15674	15077	12954	18994	13857	14617	15378
231	209			208	216	201	189		
		209	208					196	204
231	209	209	208	208	216	201	189	196	204
3.01	2.50	2.64	2.78	2.92	2.56	3.05	3.04	3.14	3.23
134.36	99.28	123.05	129.87	136.71	138.35	109.16	158.82	133.26	132.21
125.05	92.41	114.53	120.87	127.24	128.77	101.60	147.82	124.03	123.05
22	24	24	24	24	23	25	26	25	25
0.90	1.00	1.00	1.00	1.00	0.96	1.04	1.10	1.06	1.02
0.74	0.67	0.67	0.67	0.67	0.69	0.64	0.61	0.63	0.65
0.0348	0.0315	0.0315	0.0314	0.0314	0.0326	0.0303	0.0285	0.0296	0.0307
27.0	23.0	23.0	23.0	19.8	30.0	20.6	25.3	26.2	27.2
25.1	21.4	21.4	21.4	18.5	27.9	19.1	23.5	24.4	25.3
31.6	30.8	29.1	31.7	34.3	34.8	34.4	35.0	47.5	44.8
8.5	7.5	6.7	7.3	7.9	7.2	9.6	6.8	12.5	12.2

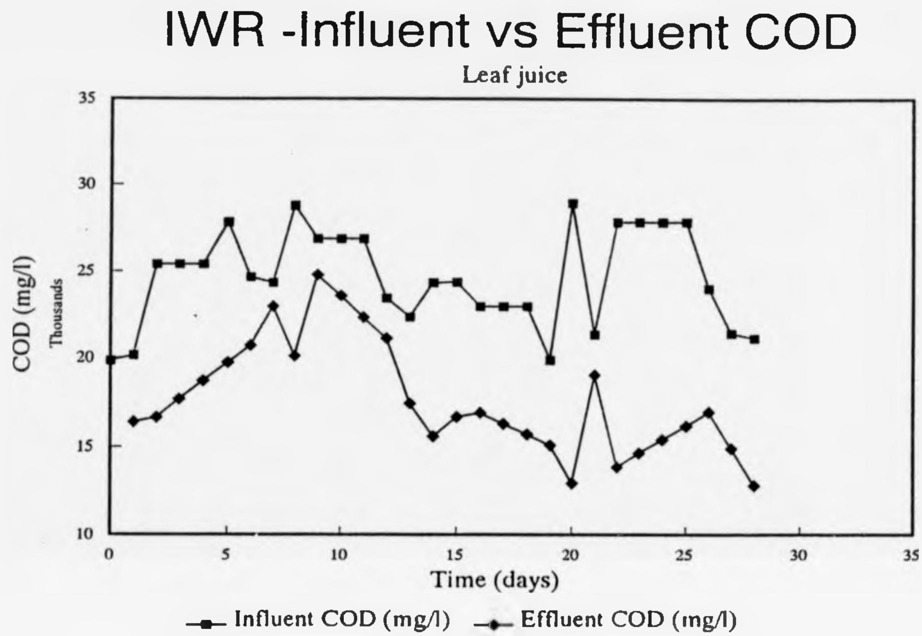
25	26	27	28
Sun	Mon	Tues	Wed
3/1/93	4/1/93	5/1/93	6/1/93
28	27	29	30
	53	35	55
	47	48	43
	17096	15023	15397
16623			
16623	17096	15023	15397
25935	22319	19888	19637
15097	15808	13923	11985
	23980	21368	21098
27865			
27865	23980	21368	21098
	16899	14884	12812
16138			
16138	16899	14884	12812
	218	203	206
211			
211	218	203	206
3.32	3.42	3.00	3.08
131.23	130.32	128.65	158.90
122.14	121.30	119.74	147.90
24	23	25	24
0.99	0.96	1.03	1.01
0.68	0.70	0.65	0.66
0.0318	0.0329	0.0306	0.0311
28.2	25.1	20.8	20.9
26.2	23.4	19.4	19.4
42.1	39.4	37.9	40.0
11.9	11.5	8.9	8.5

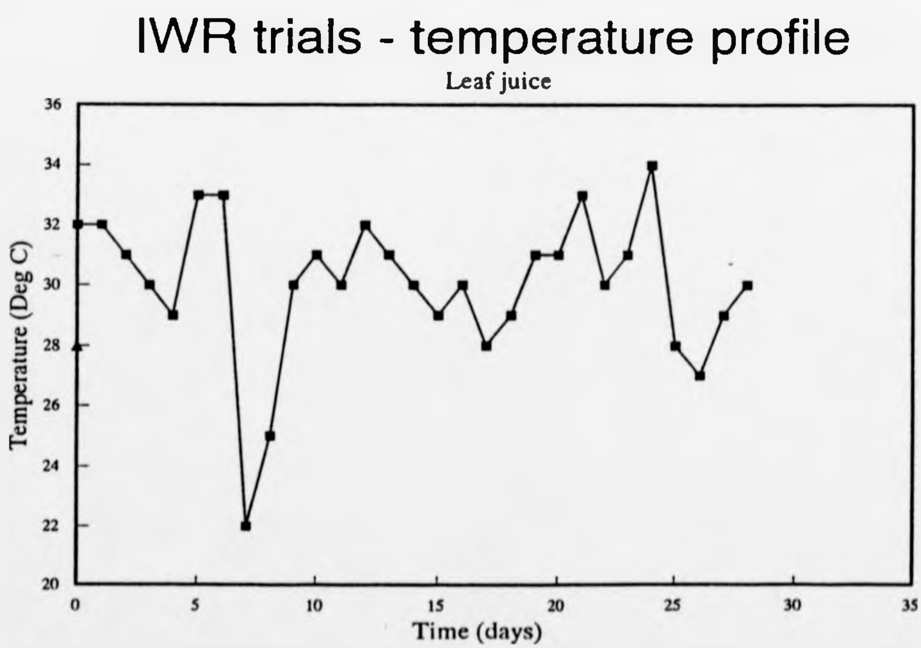
IWR - COD removal rates



IWR - Actual gas production




IWR -Influent vs Effluent COD
Leaf juice
COD (mg/l)
Thousands
35
30
25
20
15
10
0
5
10
15
20
25
30
35
Time (days)
Influent COD (mg/l)
Effluent COD (mg/l)


IWR trials - temperature profile
Leaf juice
Temperature (Deg C)
36
34
32
30
28
26
24
22
20
0
5
10
15
20
25
30
35
Time (days)

*** RUN NUMBER 4 ***

ENERGY FROM BIOMASS VIA METHANE
Results obtained from an IWR in Bangkok, 1992
Liquid volume of digester = 5 litres
Gas volume of digester = 0.162 litres

MONITORED PARAMETERS

Day from start	0	1	2	3	4
Whole plant juice	Wed	Thur	Fri	Sat	Sun
Sart date: 2/12/92	2/12/92	3/12/92	4/12/92	5/12/92	6/12/92
Ambient temperature (Deg C)	33	32	34	31	32
CH4 (%)		7	9		
CO2 (%)		12	16		
Volume of biogas produced per day (ml)		144	279		
Estimated gas production (ml)				1077	1875
Actual with estimate gas production (ml)		144	279	1077	1875
Influent volatile Solids (Measures values)(mg/l)	9641	9873			
Influent volatile Solids (Calculated values)(mg/l)	9641	9786	10216	10216	10216
Effluent volatile solids (Measured values)(mg/l)		8578			
Effluent volatile solids (Calculated values)(mg/l)		8578	7875	7192	6509
Influent total Solids (mg/l)		17523			
Effluent total solids (mg/l)		13381			
INPUT COD (mg/l)	11704	11881	12402		
Estimated values (mg/l)				12402	12402
Actuals with estimates (mg/l)	11704	11881	12402	12402	12402
OUTPUT COD (mg/l)		10491	9631		
Estimated values (mg/l)				8796	7960
Actuals with estimates (mg/l)		10491	9631	8796	7960
Actual influent flow rate (ml/hr)	48	53	51		
Estimate influent flow rate (ml/hr)				150	150
Influent flow rate (ml/hr)	48	53	51	150	150

CALCULATED VALUES

Gas production (l/l digester vol/day)	0.00	0.03	0.06	0.22	0.38
Gas production (l/kg VS/day)	0.00	12.97	22.41	86.13	50.98
Gas production (l/kg COD/day)	0.00	10.68	18.46	70.95	42.00
Hydraulic retention time (hrs)	104	94	98	33	33
Hydraulic retention time (days)	4.34	3.93	4.08	1.39	1.39
Hydraulic velocity in base of riser (m/hr)	0.15	0.17	0.16	0.48	0.48
Hydraulic velocity at overflow from riser (m/hr)	0.0072	0.0080	0.0077	0.0226	0.0226
Organic loading (kg COD/m3/day)	2.7	3.0	3.0	8.9	8.9
Organic loading (kg VS/m3/day)	2.2	2.5	2.5	7.4	7.4
COD removal efficiency (%)		10.4	18.9	29.1	35.8

5	6	7	8	9	10	11	12	13	14
Mon	Tues	Wed	Thur	Fri	Sat	Sun	Mon	Tues	Wed
7/12/92	8/12/92	9/12/92	10/12/92	11/12/92	12/12/92	13/12/92	14/12/92	15/12/92	16/12/92
28	33	32	32	31	30	29	33	33	22
32	44	46	52	43			55	57	52
42	49	51	43	43			44	42	46
2673	3699	3157	2876	4144			4417	4176	1796
					4235	4326			
2673	3699	3157	2876	4144	4235	4326	4417	4176	1796
11155	10703	10259	10848	10802	10802	10802	9952	10223	10436
5826	6031	5766	5176	6361	6122	5884	5645	5038	8612
13542	12993	12455	13170	13114			12081	12411	12670
					13114	13114			
13542	12993	12455	13170	13114	13114	13114	12081	12411	12670
7125	7376	7051	6330	7779			6904	6161	10533
					7487	7196			
7125	7376	7051	6330	7779	7487	7196	6904	6161	10533
148	154	153	147	211			207	194	217
					210	208			
148	154	153	147	211	210	208	207	194	217
0.53	0.74	0.63	0.58	0.83	0.85	0.87	0.88	0.84	0.36
72.68	93.36	79.81	76.34	108.28	77.42	79.46	81.91	84.47	37.73
59.87	76.90	65.74	62.89	89.19	63.77	65.45	67.47	69.58	31.08
34	32	33	34	24	24	24	24	26	23
1.41	1.35	1.36	1.42	0.99	0.99	1.00	1.01	1.07	0.96
0.47	0.49	0.49	0.47	0.68	0.67	0.67	0.66	0.62	0.70
0.0223	0.0232	0.0231	0.0222	0.0318	0.0317	0.0314	0.0312	0.0293	0.0327
9.6	9.6	9.1	9.3	13.3	13.2	13.1	12.0	11.6	13.2
7.9	7.9	7.5	7.7	10.9	10.9	10.8	9.9	9.5	10.9
42.5	45.5	45.7	49.2	40.9	42.9	45.1	47.4	49.0	15.1

15	16	17	18	19	20	21	22	23	24
Thur	Fri	Sat	Sun	Mon	Tues	Wed	Thur	Fri	Sat
17/12/92	18/12/92	19/12/92	20/12/92	21/12/92	22/12/92	23/12/92	24/12/92	25/12/92	26/12/92
25	30	31	30	32	31	30	29	30	28
54	56			54	56	49	53	56	
45	43			45	44	50	46	44	
2375	1895			3378	4690	6950	7025	7913	
		2389	2884						8404
2375	1895	2389	2884	3378	4690	6950	7025	7913	8404
10100	10425	10425	10425	10352	11308	10052	10819	10774	10774
8185	8089	7911	7733	7554	6722	6392	4935	5141	5258
12262	12656			12568	13728	12203	13135	13080	
		12656	12656						13080
12262	12656	12656	12656	12568	13728	12203	13135	13080	13080
10010	9893			9239	8221	7817	6035	6288	
		9675	9457						6430
10010	9893	9675	9457	9239	8221	7817	6035	6288	6430
228	184			193	218	190	199	224	
		187	190						221
228	184	187	190	193	218	190	199	224	221
0.48	0.38	0.48	0.58	0.68	0.94	1.39	1.41	1.58	1.68
43.70	34.29	51.90	61.63	71.06	97.81	117.47	153.26	153.13	145.10
35.99	28.24	42.75	50.77	58.53	80.57	96.76	126.24	126.14	119.52
22	27	27	26	26	23	26	25	22	23
0.91	1.13	1.11	1.10	1.08	0.96	1.10	1.05	0.93	0.94
0.73	0.59	0.60	0.61	0.62	0.70	0.61	0.64	0.72	0.71
0.0344	0.0278	0.0282	0.0287	0.0291	0.0329	0.0287	0.0300	0.0338	0.0333
13.4	11.2	11.4	11.5	11.6	14.4	11.1	12.5	14.1	13.9
11.1	9.2	9.4	9.5	9.6	11.8	9.2	10.3	11.6	11.4
21.0	19.3	23.6	25.3	27.0	34.6	43.1	50.5	52.1	50.8

25	26	27	28	29	30	31	32	33	34
Sun	Mon	Tues	Wed	Thur	Fri	Sat	Sun	Mon	Tues
27/12/92	28/12/92	29/12/92	30/12/92	31/12/92	1/1/93	2/1/93	3/1/93	4/1/93	5/1/93
29	31	31	33	30	31	34	28	27	29
	52	47	55	57				54	55
	46	49	44	42				44	44
	9387	8445	7687	10559				9750	11304
8896					10357	10155	9952		
8896	9387	8445	7687	10559	10357	10155	9952	9750	11304
10774	10608	10605	11070	9368	9568	9767	9967	10166	9872
5374	5491	5244	4923	5055	5024	4992	4961	4929	5027
	12878	12874	13439	11373				12342	11985
13080					11615	11858	12100		
13080	12878	12874	13439	11373	11615	11858	12100	12342	11985
	6715	6413	6020	6182				6029	6148
6573					6144	6105	6067		
6573	6715	6413	6020	6182	6144	6105	6067	6029	6148
	216	211	184	215				204	227
219					212	210	207		
219	216	211	184	215	212	210	207	204	227
1.78	1.88	1.69	1.54	2.11	2.07	2.03	1.99	1.95	2.26
155.67	165.77	153.57	143.14	215.99	214.24	208.59	202.17	196.91	227.10
128.23	136.55	126.50	117.91	177.92	176.48	171.82	166.53	162.20	187.07
23	23	24	27	23	24	24	24	25	22
0.95	0.96	0.99	1.13	0.97	0.98	0.99	1.01	1.02	0.92
0.70	0.69	0.68	0.59	0.69	0.68	0.67	0.66	0.65	0.73
0.0330	0.0326	0.0318	0.0278	0.0324	0.0320	0.0317	0.0312	0.0308	0.0342
13.7	13.4	13.0	11.9	11.7	11.8	12.0	12.0	12.1	13.1
11.3	11.0	10.7	9.8	9.7	9.7	9.8	9.9	10.0	10.8
49.7	48.7	50.2	53.2	54.0	46.0	47.4	48.8	50.2	50.2

35
Wed
6/1/93

30

60
38
9840

9840

10359

4554

12576

12576
5569

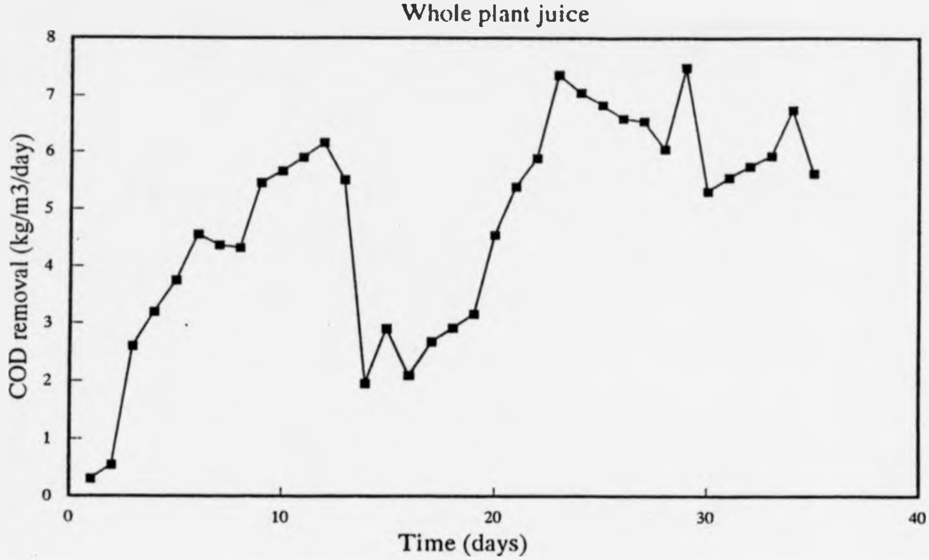
5569

183

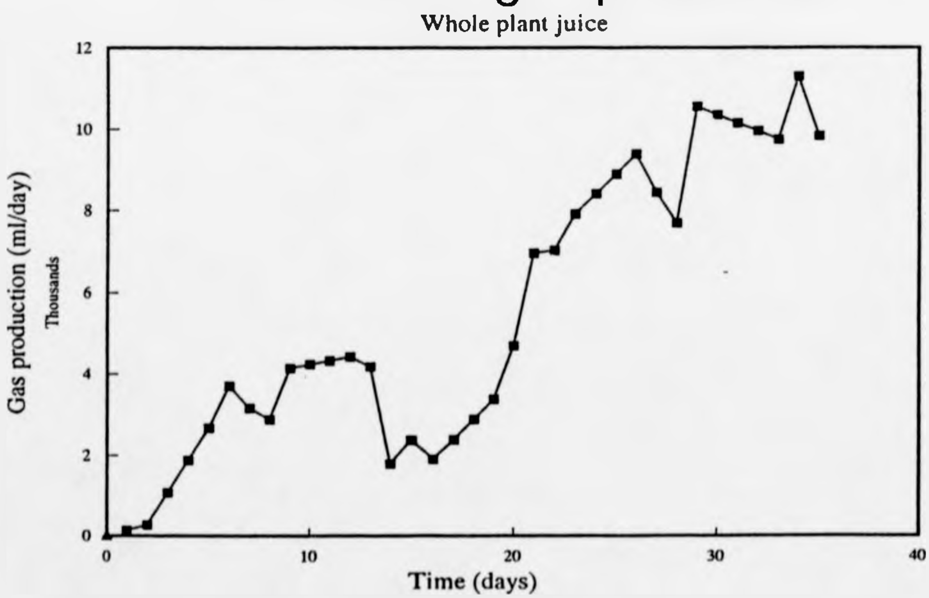
183

1.97
182.95
150.70
27
1.14
0.59
0.0276
11.0
9.1
53.5

IWR - COD removal rates

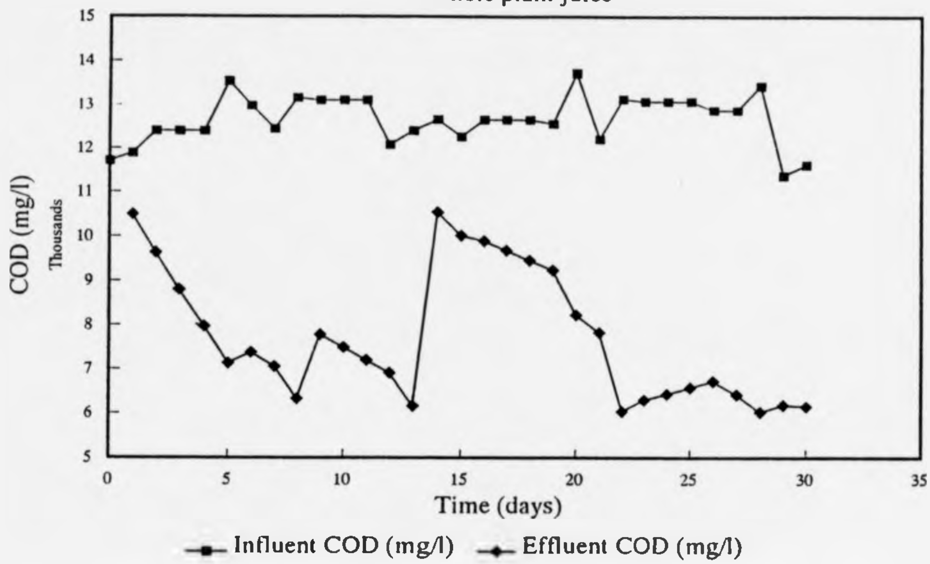


IWR - Actual gas production



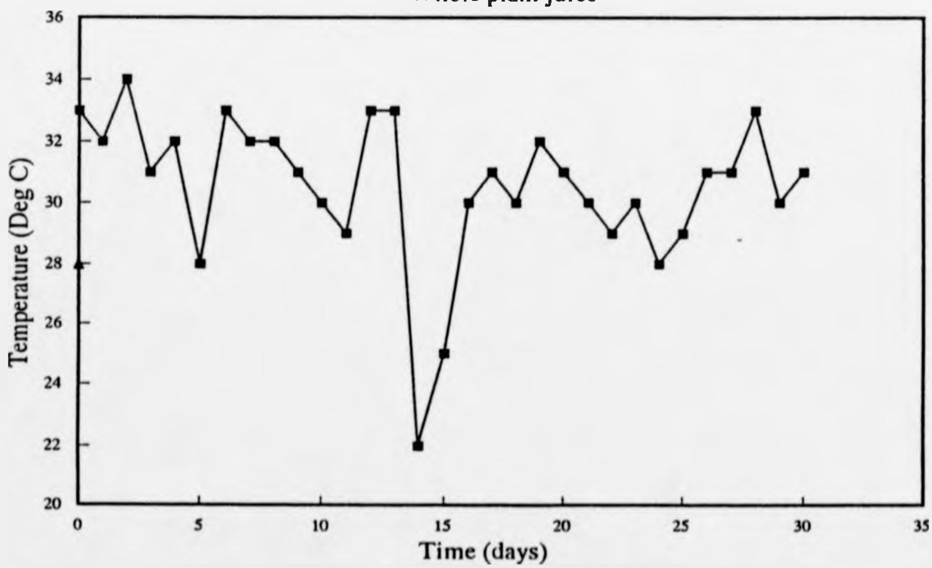
IWR -Influent vs Effluent COD

Whole plant juice



IWR trials - temperature profile

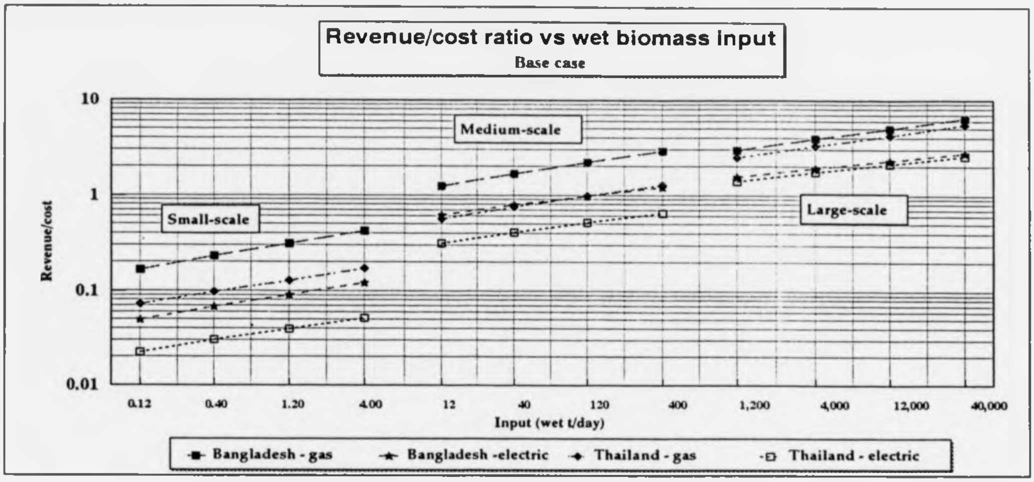
Whole plant juice

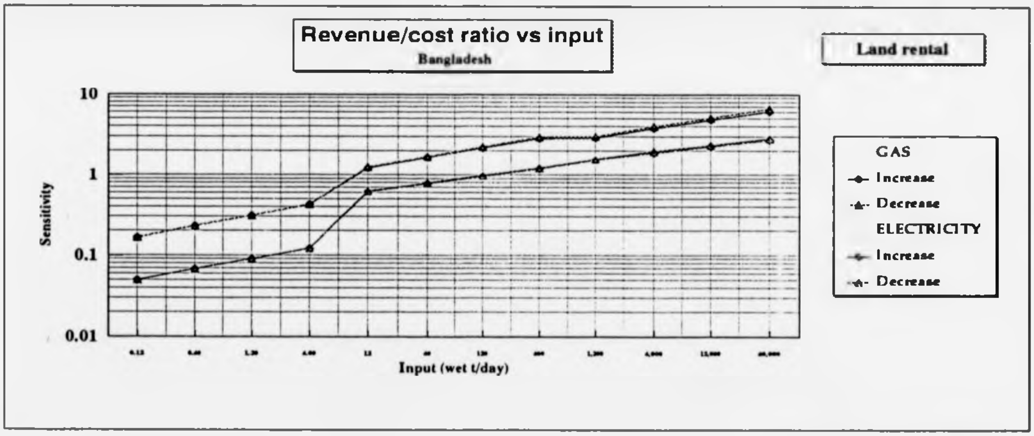


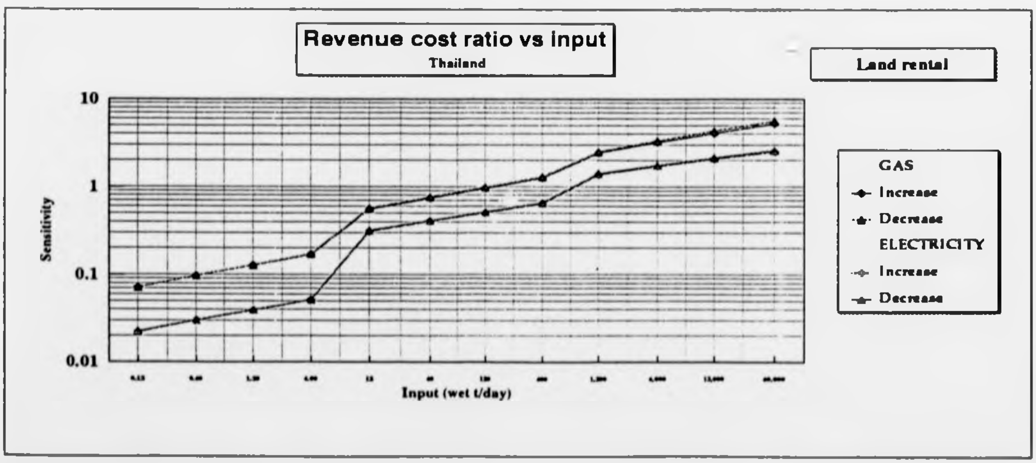
Appendix 4

Tabulated results from sensitivity analysis.

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Land rental*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREASE	%DECREASE
1. Land rental	100%	50%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Land rental
Percentage variation **(Increase)** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.23	0.31	0.43	1.23	1.66	2.16	2.84	2.89	3.80	4.80	6.07
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.17	0.23	0.31	0.43	1.25	1.70	2.22	2.93	3.00	4.00	5.12	6.59
Bangladesh - electricity production	Increase	100%	0.05	0.07	0.09	0.12	0.61	0.78	0.97	1.20	1.54	1.90	2.26	2.70
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.09	0.12	0.62	0.80	0.99	1.23	1.58	1.95	2.34	2.81
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.17	0.56	0.75	0.96	1.26	2.42	3.21	4.10	5.23
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.57	0.76	0.99	1.29	2.50	3.35	4.33	5.62
Thailand - electricity production	Increase	100%	0.02	0.03	0.04	0.05	0.31	0.41	0.51	0.64	1.38	1.72	2.08	2.51
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.66	1.41	1.77	2.14	2.60

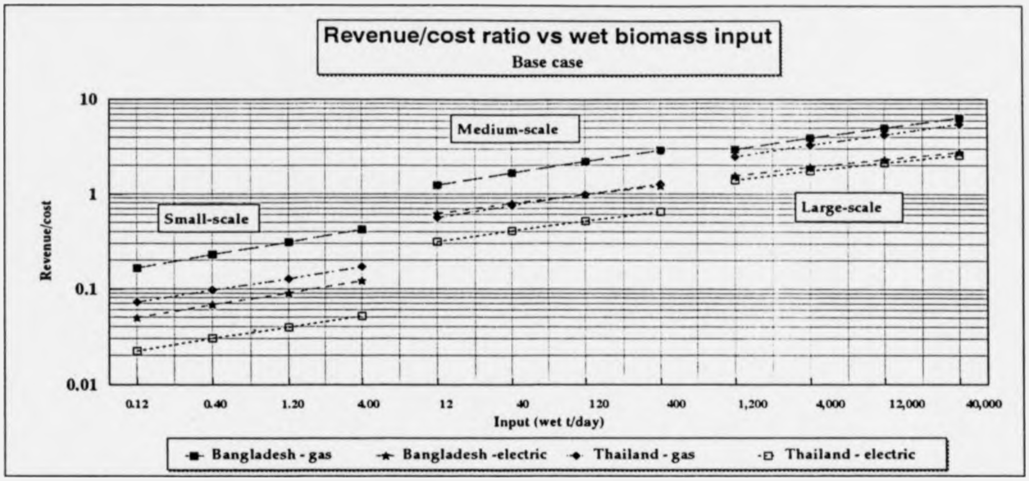
SENSITIVITY

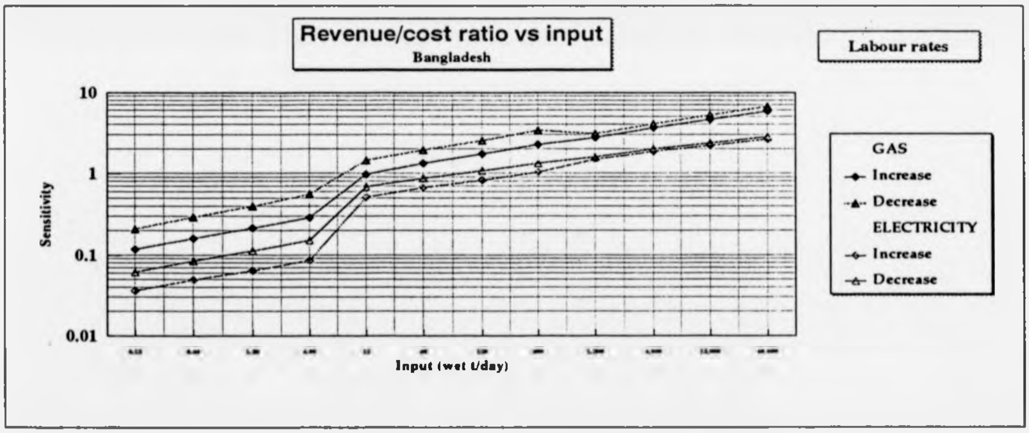
<u>New ratio - old ratio</u> divided by <u>New sub-item - old sub-item</u>
Old ratio old sub-item

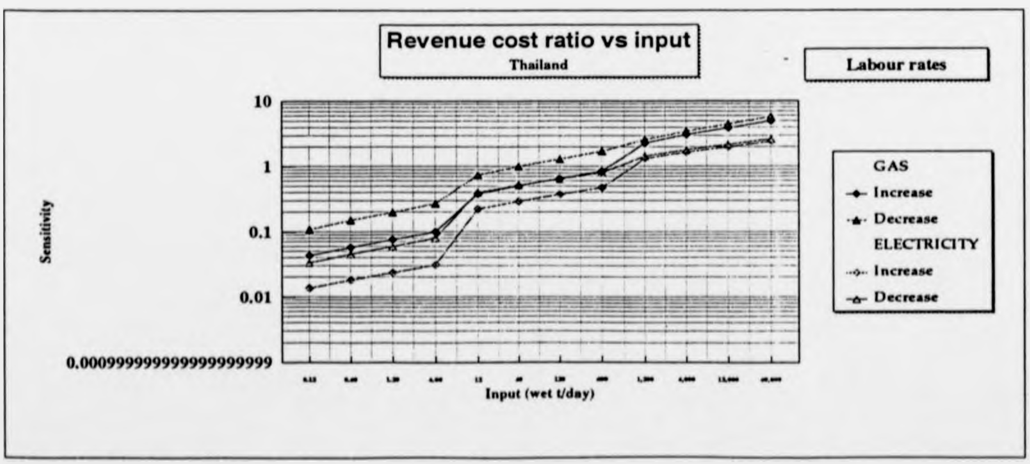
Varied parameter : Land rental

		Percent change												
Bangladesh - gas production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.01	-0.01	-0.02	-0.02	-0.03	-0.03	-0.04	-0.05
	Decrease	50%	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.06
Bangladesh - electricity production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.03
	Decrease	50%	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03
Thailand - gas production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.03	-0.04	-0.05
	Decrease	50%	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.05
Thailand - electricity production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.02
	Decrease	50%	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Labour rates*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	100%	50%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Labour rates

Percentage variation **(Increase** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.12	0.16	0.21	0.29	0.98	1.32	1.72	2.27	2.76	3.64	4.61	5.85
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.21	0.29	0.40	0.56	1.44	1.95	2.55	3.37	3.07	4.09	5.24	6.73
Bangladesh - electricity production	Increase	100%	0.04	0.05	0.06	0.09	0.52	0.67	0.83	1.04	1.50	1.85	2.21	2.64
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.06	0.08	0.11	0.15	0.69	0.87	1.08	1.33	1.60	1.98	2.37	2.85
Thailand - gas production	Increase	100%	0.04	0.06	0.08	0.10	0.38	0.51	0.66	0.86	2.30	3.05	3.88	4.95
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.11	0.15	0.20	0.27	0.75	1.00	1.30	1.71	2.56	3.45	4.46	5.80
Thailand - electricity production	Increase	100%	0.01	0.02	0.02	0.03	0.22	0.29	0.37	0.47	1.34	1.66	2.01	2.42
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.03	0.05	0.06	0.08	0.40	0.51	0.64	0.81	1.44	1.80	2.18	2.65

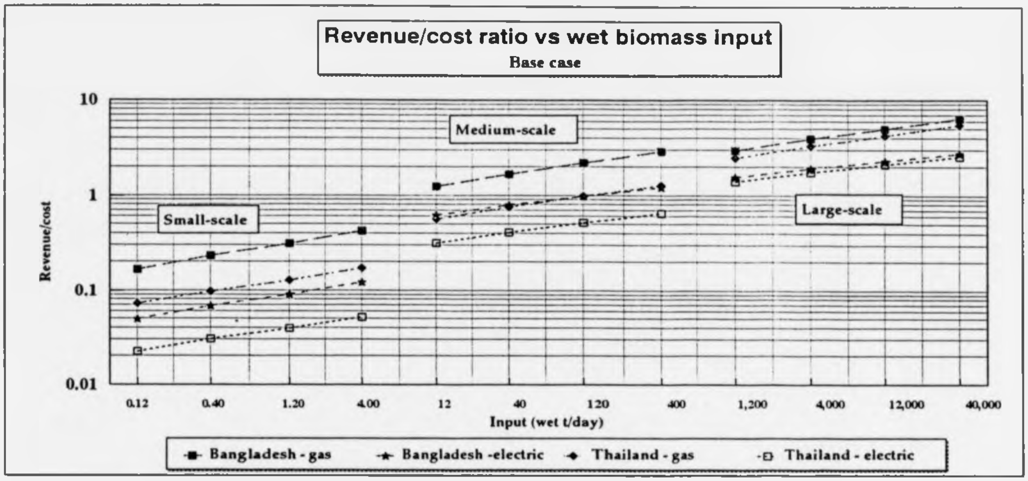
SENSITIVITY

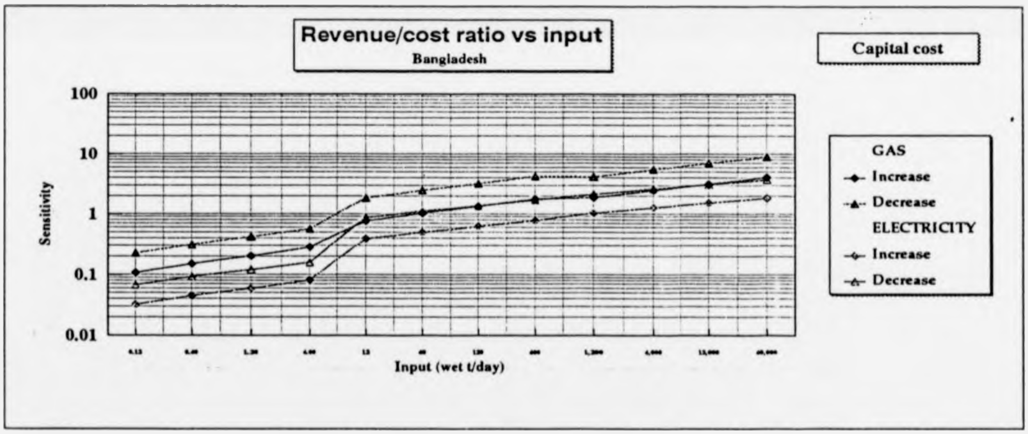
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

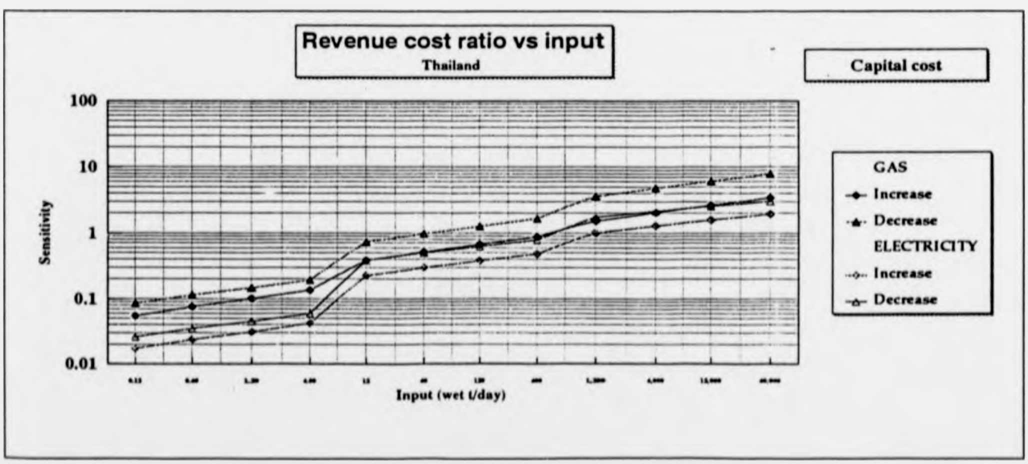
Varied parameter : Labour rates

		Percent change												
Bangladesh - gas production	Increase	100%	-0.29	-0.30	-0.31	-0.32	-0.21	-0.21	-0.22	-0.22	-0.07	-0.07	-0.08	-0.09
	Decrease	50%	0.51	0.54	0.57	0.61	0.31	0.32	0.32	0.32	0.07	0.08	0.09	0.10
Bangladesh - electricity production	Increase	100%	-0.28	-0.28	-0.29	-0.29	-0.16	-0.16	-0.15	-0.15	-0.04	-0.04	-0.05	-0.05
	Decrease	50%	0.47	0.49	0.51	0.53	0.22	0.21	0.20	0.19	0.05	0.05	0.05	0.05
Thailand - gas production	Increase	100%	-0.40	-0.41	-0.41	-0.42	-0.33	-0.33	-0.33	-0.33	-0.07	-0.08	-0.09	-0.10
	Decrease	50%	1.02	1.06	1.10	1.15	0.64	0.65	0.66	0.66	0.08	0.09	0.10	0.11
Thailand - electricity production	Increase	100%	-0.40	-0.40	-0.40	-0.41	-0.29	-0.29	-0.28	-0.28	-0.05	-0.05	-0.05	-0.06
	Decrease	50%	0.97	1.00	1.03	1.06	0.51	0.50	0.49	0.47	0.05	0.05	0.06	0.06

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter : *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Capital cost*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	100%	50%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Capital cost
Percentage variation **(Increase** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.11	0.15	0.21	0.29	0.76	1.03	1.34	1.77	1.88	2.50	3.19	4.07
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.23	0.31	0.42	0.56	1.83	2.47	3.22	4.25	4.15	5.51	7.03	9.00
Bangladesh - electricity production	Increase	100%	0.03	0.04	0.06	0.08	0.39	0.50	0.62	0.78	1.03	1.27	1.52	1.83
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.07	0.09	0.12	0.16	0.87	1.12	1.37	1.70	2.12	2.61	3.12	3.74
Thailand - gas production	Increase	100%	0.06	0.08	0.10	0.14	0.39	0.52	0.67	0.88	1.52	2.04	2.63	3.41
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.08	0.11	0.15	0.20	0.73	0.98	1.27	1.65	3.61	4.80	6.14	7.89
Thailand - electricity production	Increase	100%	0.02	0.02	0.03	0.04	0.23	0.30	0.38	0.49	1.01	1.29	1.58	1.95
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.03	0.04	0.05	0.06	0.39	0.50	0.63	0.79	1.74	2.14	2.55	3.04

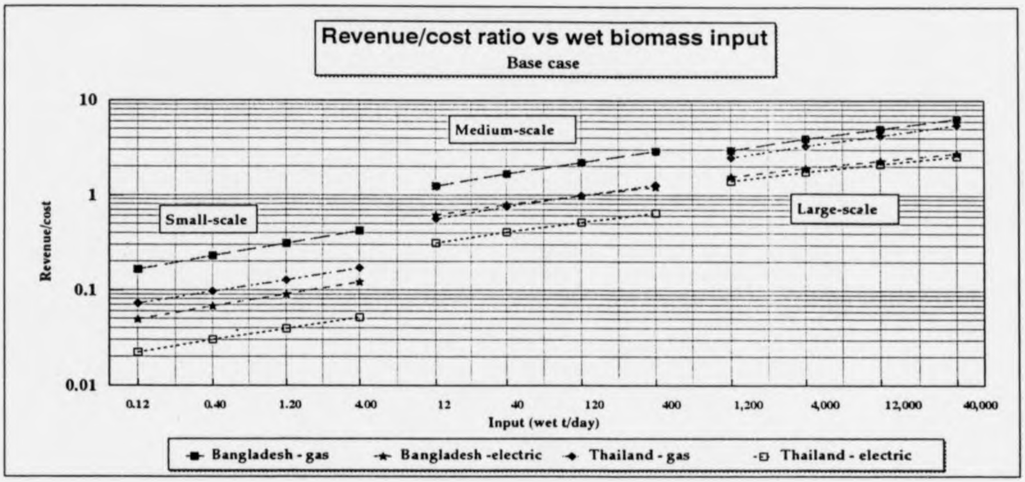
SENSITIVITY

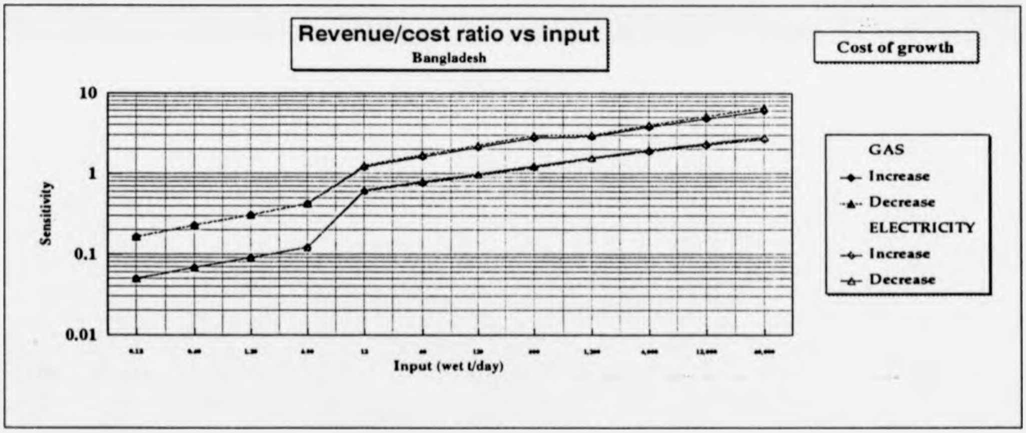
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

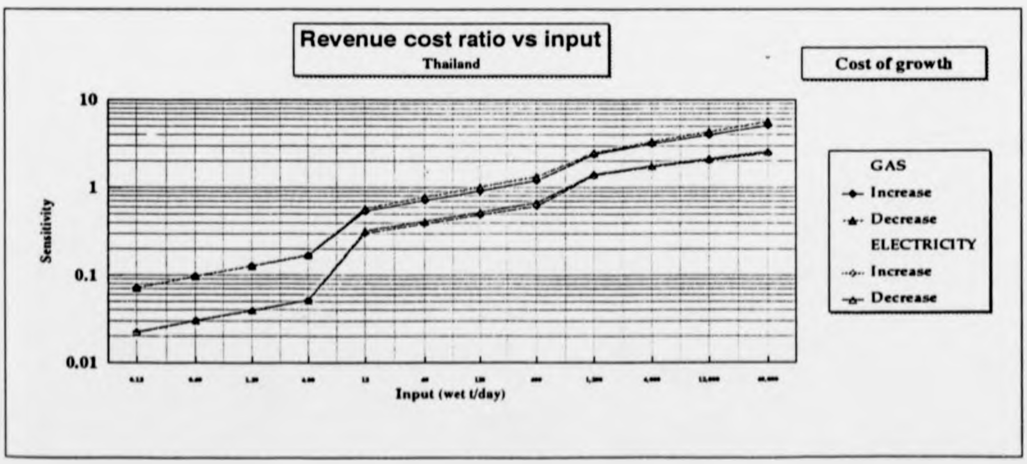
Varied parameter : Capital cost

		Percent change												
Bangladesh - gas production	Increase	100%	-0.35	-0.35	-0.34	-0.33	-0.39	-0.39	-0.39	-0.39	-0.36	-0.36	-0.36	-0.37
	Decrease	50%	0.75	0.72	0.69	0.65	0.93	0.93	0.93	0.93	0.80	0.80	0.80	0.81
Bangladesh - electricity production	Increase	100%	-0.35	-0.34	-0.34	-0.33	-0.37	-0.37	-0.36	-0.36	-0.34	-0.34	-0.34	-0.34
	Decrease	50%	0.74	0.71	0.68	0.64	0.83	0.82	0.80	0.79	0.71	0.70	0.70	0.69
Thailand - gas production	Increase	100%	-0.23	-0.22	-0.21	-0.20	-0.32	-0.31	-0.31	-0.31	-0.39	-0.38	-0.38	-0.38
	Decrease	50%	0.36	0.34	0.31	0.29	0.60	0.59	0.59	0.58	0.92	0.91	0.89	0.88
Thailand - electricity production	Increase	100%	-0.23	-0.22	-0.21	-0.19	-0.28	-0.27	-0.26	-0.26	-0.28	-0.27	-0.25	-0.24
	Decrease	50%	0.35	0.32	0.30	0.27	0.48	0.46	0.44	0.41	0.49	0.44	0.41	0.37

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Growth*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	100%	50%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Growth

Percentage variation **(Increase)** 100% **(Decrease)** 50%

			Wet input (t/d) 0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.23	0.31	0.43	1.21	1.63	2.11	2.77	2.88	3.79	4.78	6.04
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.17	0.23	0.31	0.43	1.26	1.72	2.24	2.97	3.00	4.01	5.14	6.62
Bangladesh - electricity production	Increase	100%	0.05	0.07	0.09	0.12	0.61	0.77	0.95	1.18	1.54	1.89	2.26	2.70
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.09	0.12	0.62	0.80	0.99	1.24	1.58	1.95	2.34	2.82
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.17	0.54	0.72	0.92	1.19	2.40	3.18	4.04	5.15
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.58	0.78	1.01	1.33	2.51	3.37	4.36	5.67
Thailand - electricity production	Increase	100%	0.02	0.03	0.04	0.05	0.30	0.39	0.49	0.62	1.38	1.71	2.06	2.48
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.32	0.42	0.53	0.67	1.42	1.77	2.15	2.61

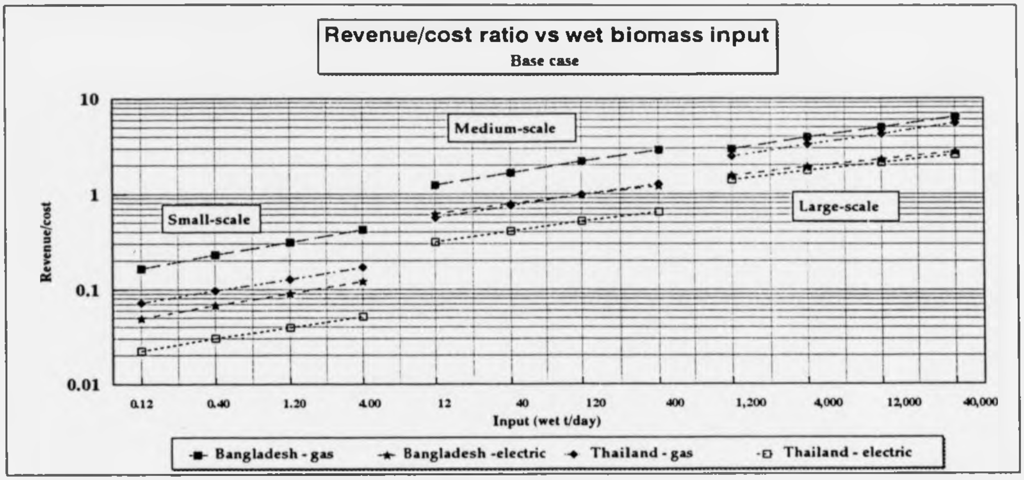
SENSITIVITY

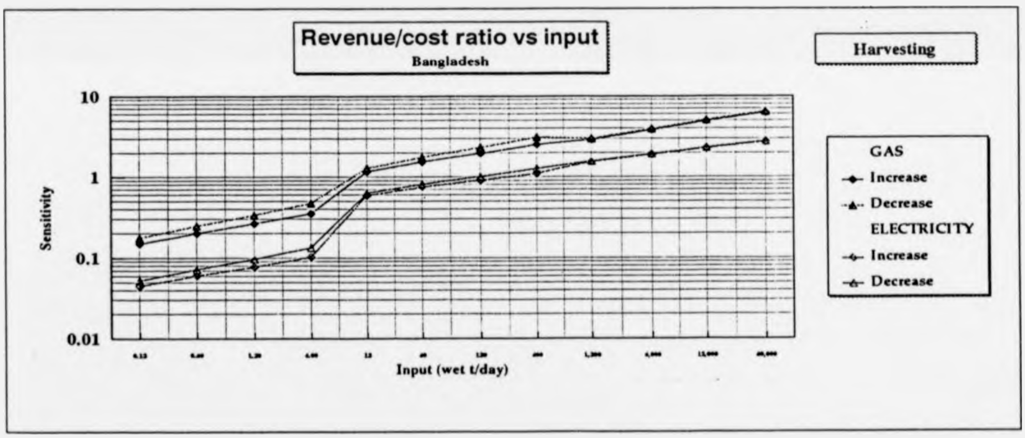
<u>New ratio - old ratio</u> divided by <u>New sub-item - old sub-item</u>
Old ratio old sub-item

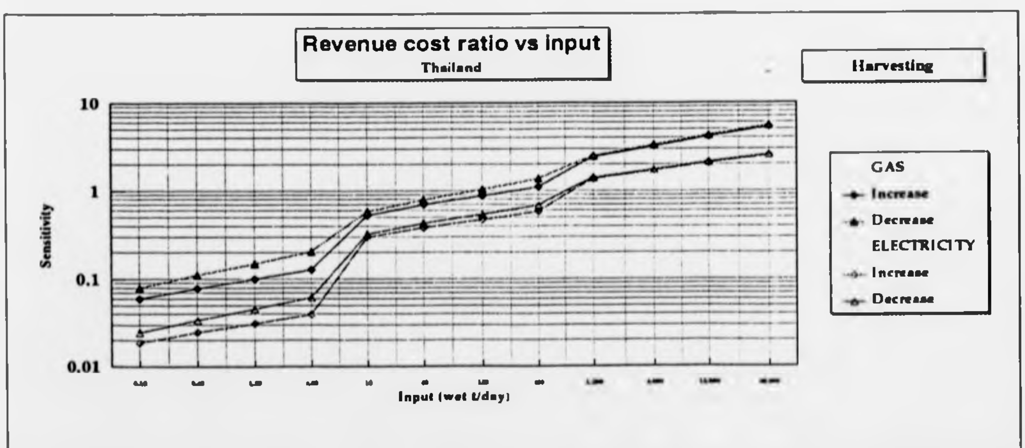
Varied parameter : Growth

		Percent change												
Bangladesh - gas production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.03	-0.03	-0.04	-0.05	-0.03	-0.04	-0.05	-0.06
	Decrease	50%	0.00	0.00	0.00	0.00	0.03	0.04	0.04	0.05	0.03	0.04	0.05	0.06
Bangladesh - electricity production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.02	-0.02	-0.03	-0.03	-0.02	-0.02	-0.02	-0.03
	Decrease	50%	0.00	0.00	0.00	0.00	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.03
Thailand - gas production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.04	-0.05	-0.06	-0.07	-0.03	-0.04	-0.05	-0.06
	Decrease	50%	0.00	0.00	0.00	0.00	0.05	0.06	0.07	0.08	0.03	0.04	0.05	0.07
Thailand - electricity production	Increase	100%	-0.00	-0.00	-0.00	-0.00	-0.04	-0.04	-0.05	-0.05	-0.02	-0.02	-0.03	-0.03
	Decrease	50%	0.00	0.00	0.00	0.00	0.04	0.05	0.05	0.06	0.02	0.02	0.03	0.03

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2 Labour rates	0%	2. Gas price	0%
3 Capital costs	0%	3. Fertiliser price	0%
4 Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8 Cost of storage	0%		
9 Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Harvesting*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREA!	%DECREA!
1. Land rental	0%	0%	1. Electricity price	0%	0%
2 Labour rates	0%	0%	2 Gas price	0%	0%
3 Capital costs	0%	0%	3 Fertiliser price	0%	0%
4 Cost of growth	0%	0%	4. Fibre price	0%	0%
5 Cost of harvesting	100%	50%			
6 Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9 Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Harvesting
Percentage variation **(Increase)** 100% **(Decrease)** 50%

			Wet input (t/d) 0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.15	0.20	0.27	0.35	1.17	1.55	1.97	2.52	2.92	3.87	4.93	6.28
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.18	0.25	0.34	0.48	1.29	1.76	2.33	3.14	2.98	3.96	5.06	6.48
Bangladesh - electricity production	Increase	100%	0.04	0.06	0.08	0.10	0.59	0.75	0.91	1.12	1.55	1.92	2.29	2.75
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.10	0.13	0.63	0.82	1.02	1.28	1.57	1.94	2.32	2.79
Thailand - gas production	Increase	100%	0.06	0.08	0.10	0.13	0.53	0.70	0.88	1.11	2.42	3.23	4.13	5.32
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.08	0.11	0.15	0.21	0.58	0.79	1.04	1.39	2.49	3.35	4.31	5.57
Thailand - electricity production	Increase	100%	0.02	0.02	0.03	0.04	0.30	0.38	0.47	0.58	1.38	1.73	2.09	2.53
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.05	0.06	0.32	0.43	0.54	0.69	1.41	1.77	2.13	2.59

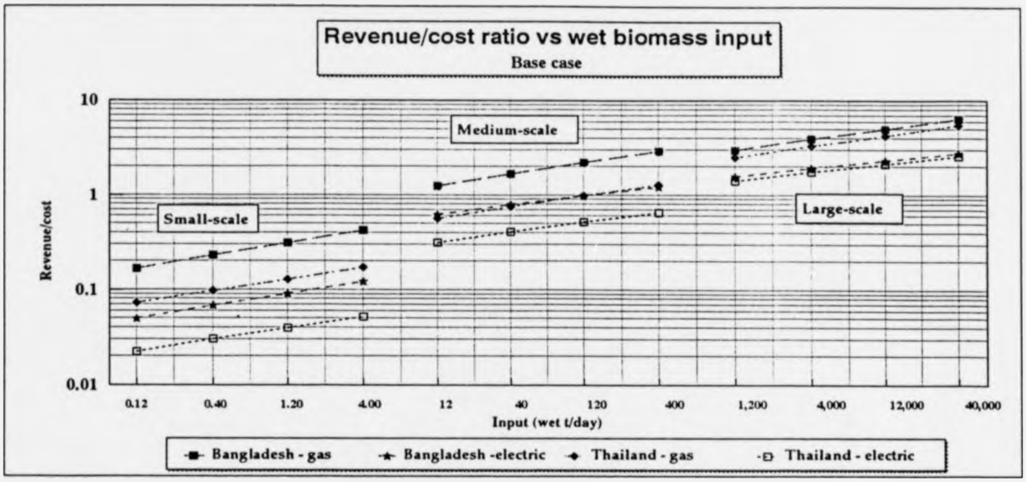
SENSITIVITY

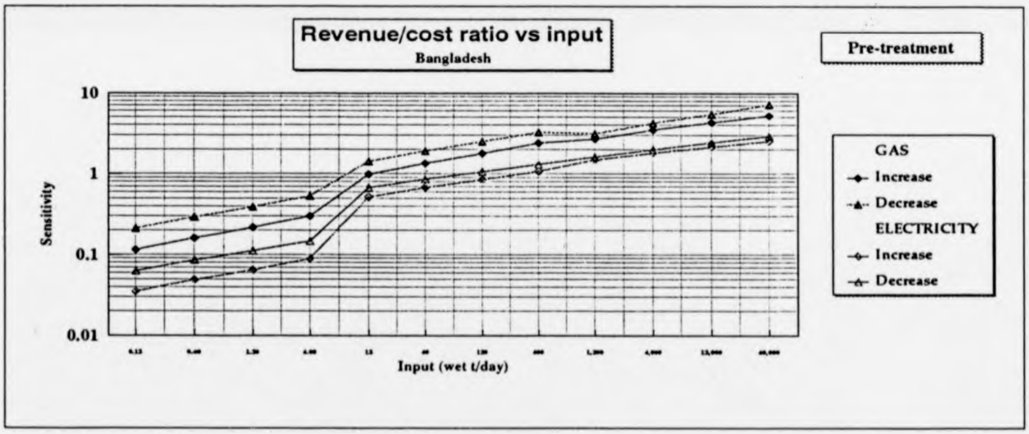
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

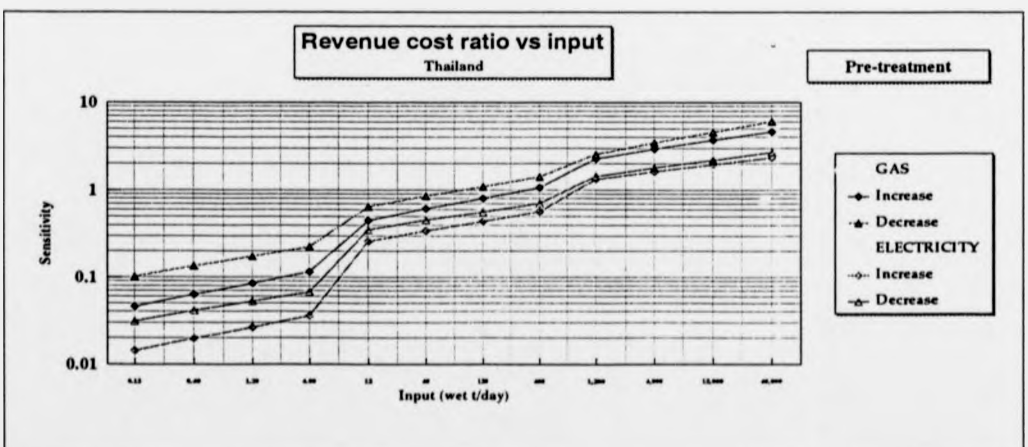
Varied parameter : Harvesting

		Percent change												
Bangladesh - gas production	Increase	100%	-0.10	-0.12	-0.15	-0.17	-0.06	-0.08	-0.10	-0.13	-0.01	-0.02	-0.02	-0.02
	Decrease	50%	0.12	0.15	0.19	0.23	0.07	0.09	0.12	0.16	0.01	0.02	0.02	0.02
Bangladesh - electricity production	Increase	100%	-0.10	-0.12	-0.13	-0.16	-0.04	-0.06	-0.07	-0.08	-0.01	-0.01	-0.01	-0.01
	Decrease	50%	0.11	0.14	0.17	0.20	0.05	0.06	0.08	0.10	0.01	0.01	0.01	0.01
Thailand - gas production	Increase	100%	-0.17	-0.19	-0.22	-0.25	-0.06	-0.08	-0.10	-0.13	-0.02	-0.02	-0.03	-0.03
	Decrease	50%	0.22	0.27	0.33	0.40	0.07	0.09	0.12	0.16	0.02	0.02	0.03	0.03
Thailand - electricity production	Increase	100%	-0.16	-0.19	-0.21	-0.24	-0.05	-0.07	-0.08	-0.10	-0.01	-0.01	-0.01	-0.02
	Decrease	50%	0.21	0.26	0.31	0.38	0.06	0.08	0.10	0.12	0.01	0.01	0.02	0.02

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Pre-treatment*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREASE	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	100%	50%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Pre-treatment
Percentage variation **(Increase)** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.11	0.16	0.22	0.30	0.99	1.35	1.78	2.39	2.69	3.47	4.28	5.26
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.21	0.30	0.39	0.53	1.43	1.92	2.49	3.25	3.12	4.21	5.48	7.20
Bangladesh - electricity production	Increase	100%	0.04	0.05	0.07	0.09	0.52	0.68	0.85	1.08	1.48	1.80	2.13	2.51
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.06	0.09	0.11	0.15	0.68	0.86	1.06	1.30	1.61	2.01	2.42	2.93
Thailand - gas production	Increase	100%	0.05	0.06	0.08	0.12	0.45	0.61	0.80	1.07	2.27	2.96	3.70	4.60
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.10	0.13	0.17	0.22	0.65	0.86	1.10	1.42	2.58	3.51	4.59	6.06
Thailand - electricity production	Increase	100%	0.01	0.02	0.03	0.04	0.26	0.34	0.44	0.57	1.33	1.64	1.96	2.34
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.03	0.04	0.05	0.07	0.35	0.45	0.56	0.71	1.44	1.81	2.21	2.70

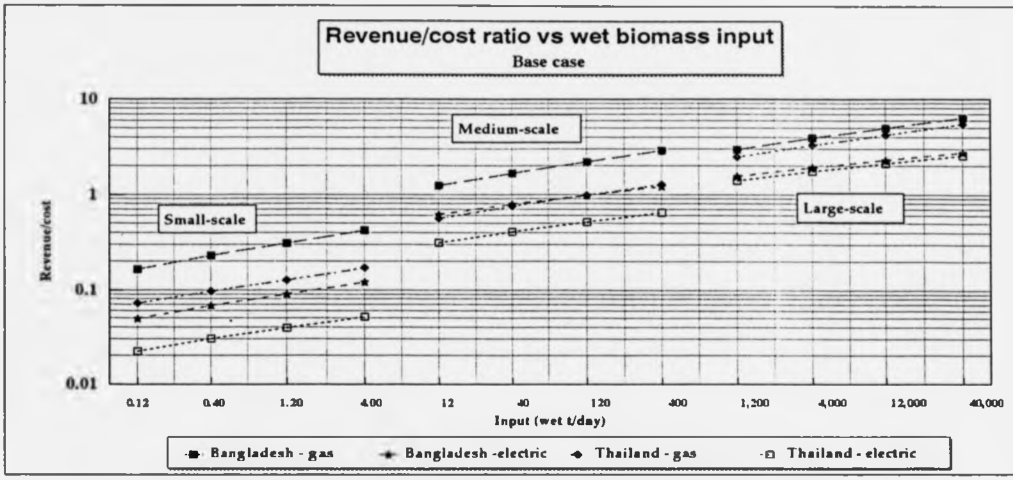
SENSITIVITY

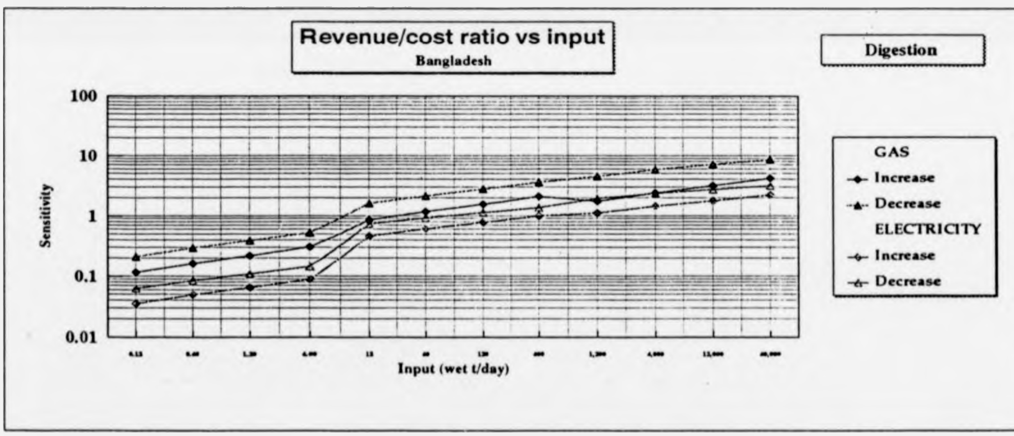
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

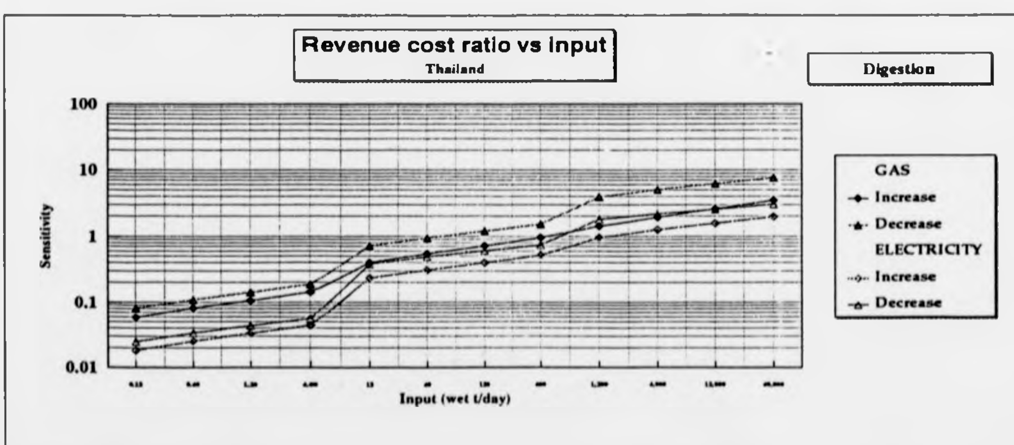
Varied parameter : Pre-treatment

		Percent change												
Bangladesh - gas production	Increase	100%	-0.31	-0.30	-0.30	-0.29	-0.21	-0.20	-0.19	-0.18	-0.09	-0.12	-0.15	-0.18
	Decrease	50%	0.58	0.56	0.53	0.50	0.30	0.28	0.26	0.24	0.11	0.14	0.19	0.25
Bangladesh - electricity production	Increase	100%	-0.30	-0.29	-0.28	-0.26	-0.16	-0.14	-0.13	-0.11	-0.06	-0.07	-0.08	-0.09
	Decrease	50%	0.53	0.50	0.47	0.43	0.21	0.18	0.16	0.14	0.06	0.07	0.09	0.11
Thailand - gas production	Increase	100%	-0.37	-0.35	-0.34	-0.32	-0.20	-0.19	-0.18	-0.17	-0.08	-0.10	-0.13	-0.16
	Decrease	50%	0.81	0.75	0.70	0.63	0.29	0.27	0.25	0.22	0.09	0.12	0.16	0.21
Thailand - electricity production	Increase	100%	-0.36	-0.35	-0.33	-0.31	-0.17	-0.16	-0.15	-0.13	-0.05	-0.06	-0.07	-0.09
	Decrease	50%	0.78	0.72	0.66	0.59	0.24	0.21	0.19	0.17	0.06	0.07	0.08	0.10

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Digestion*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	100%	50%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Digestion

Percentage variation **(Increase** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.12	0.16	0.22	0.31	0.85	1.18	1.56	2.11	1.74	2.39	3.15	4.20
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.21	0.29	0.39	0.53	1.62	2.15	2.76	3.57	4.54	5.80	7.12	8.71
Bangladesh - electricity production	Increase	100%	0.04	0.05	0.07	0.09	0.47	0.61	0.78	0.99	1.11	1.43	1.78	2.22
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.06	0.08	0.11	0.15	0.74	0.93	1.13	1.37	1.96	2.34	2.72	3.17
Thailand - gas production	Increase	100%	0.06	0.08	0.11	0.14	0.40	0.54	0.72	0.96	1.42	1.96	2.60	3.49
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.08	0.11	0.14	0.19	0.71	0.94	1.20	1.54	3.91	5.03	6.22	7.67
Thailand - electricity production	Increase	100%	0.02	0.03	0.03	0.04	0.23	0.31	0.40	0.52	0.96	1.25	1.57	1.99
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.03	0.03	0.04	0.06	0.38	0.49	0.60	0.75	1.82	2.19	2.56	3.01

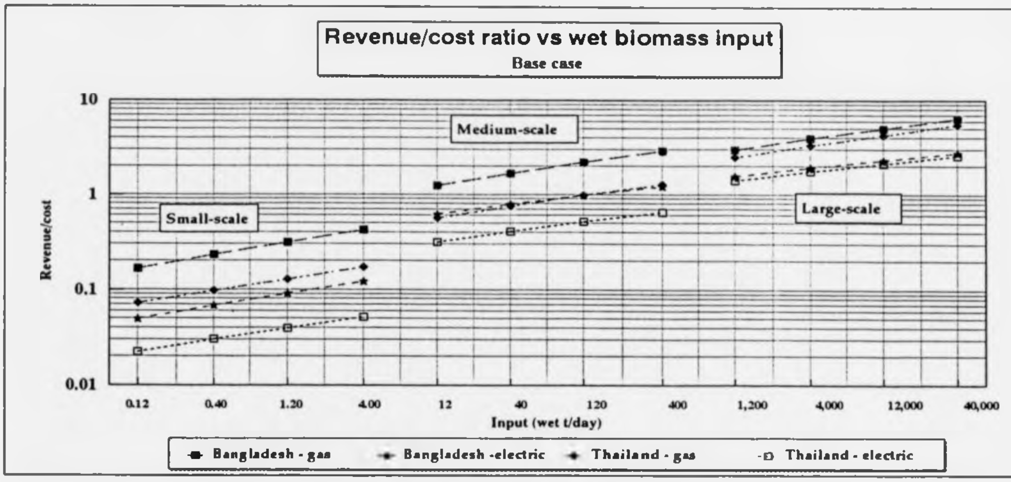
SENSITIVITY

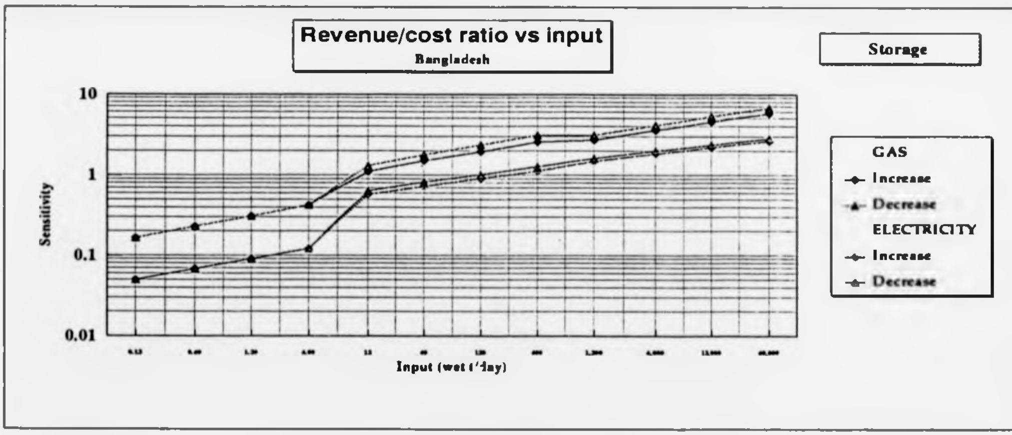
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

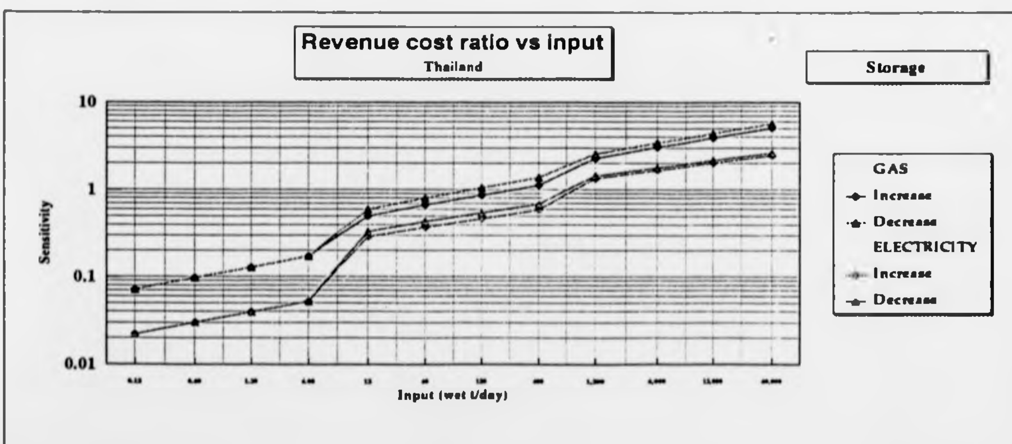
Varied parameter : Digestion

		Percent change												
Bangladesh - gas production	Increase	100%	-0.30	-0.30	-0.29	-0.28	-0.31	-0.30	-0.29	-0.27	-0.41	-0.39	-0.37	-0.35
	Decrease	50%	0.56	0.54	0.51	0.48	0.60	0.55	0.51	0.46	1.07	0.95	0.84	0.72
Bangladesh - electricity production	Increase	100%	-0.29	-0.28	-0.27	-0.26	-0.25	-0.23	-0.21	-0.18	-0.29	-0.26	-0.23	-0.20
	Decrease	50%	0.51	0.48	0.45	0.42	0.39	0.34	0.30	0.26	0.51	0.42	0.35	0.29
Thailand - gas production	Increase	100%	-0.18	-0.17	-0.17	-0.16	-0.30	-0.28	-0.27	-0.25	-0.42	-0.41	-0.39	-0.36
	Decrease	50%	0.25	0.24	0.22	0.20	0.53	0.49	0.45	0.40	1.16	1.04	0.93	0.80
Thailand - electricity production	Increase	100%	-0.18	-0.17	-0.16	-0.15	-0.26	-0.24	-0.22	-0.20	-0.31	-0.29	-0.26	-0.23
	Decrease	50%	0.24	0.23	0.21	0.19	0.43	0.38	0.34	0.29	0.59	0.50	0.42	0.34

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Storage*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	100%	50%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Storage
Percentage variation **(Increase)** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.23	0.31	0.43	1.12	1.50	1.95	2.56	2.70	3.57	4.55	5.81
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.17	0.23	0.31	0.43	1.32	1.79	2.35	3.11	3.11	4.14	5.28	6.76
Bangladesh - electricity production	Increase	100%	0.05	0.07	0.09	0.12	0.57	0.73	0.91	1.13	1.48	1.83	2.20	2.65
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.09	0.12	0.64	0.83	1.02	1.27	1.61	1.99	2.37	2.84
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.17	0.50	0.67	0.86	1.13	2.30	3.06	3.93	5.06
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.60	0.81	1.05	1.38	2.57	3.44	4.43	5.72
Thailand - electricity production	Increase	100%	0.02	0.03	0.04	0.05	0.29	0.37	0.47	0.59	1.34	1.68	2.03	2.46
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.33	0.43	0.54	0.69	1.44	1.79	2.17	2.62

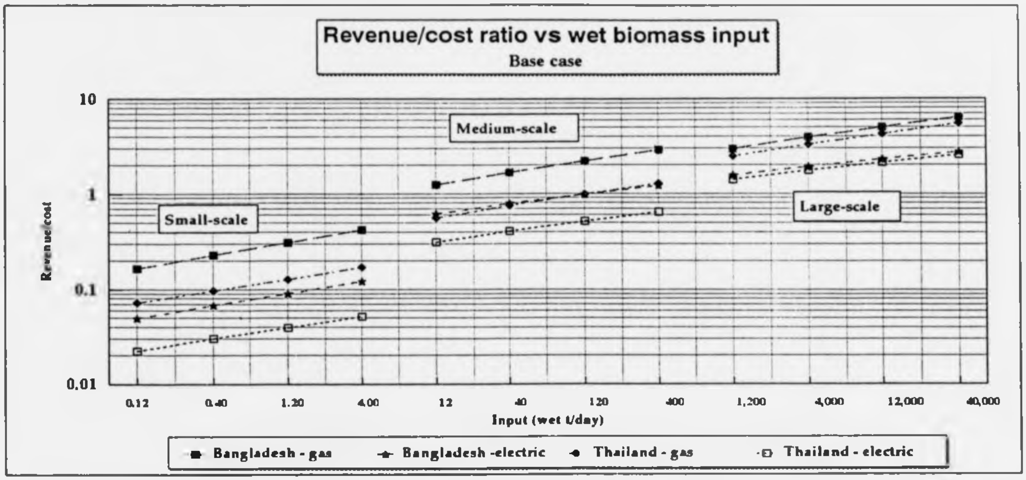
SENSITIVITY

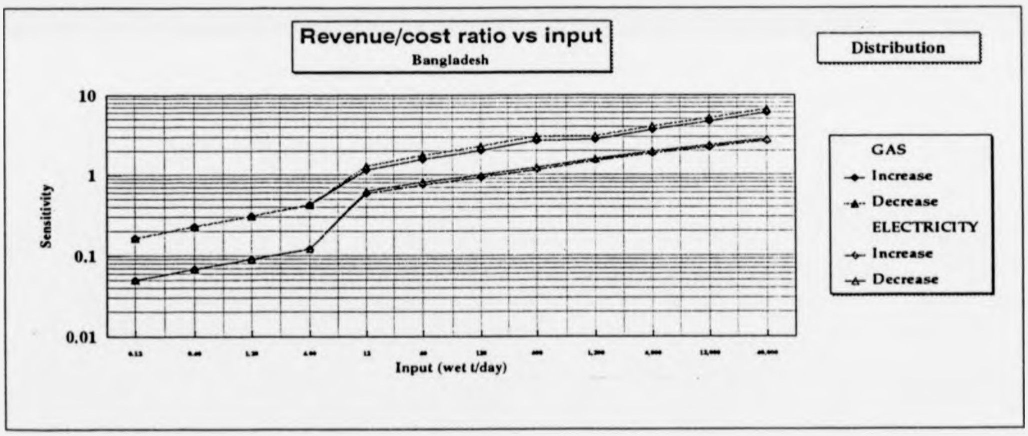
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

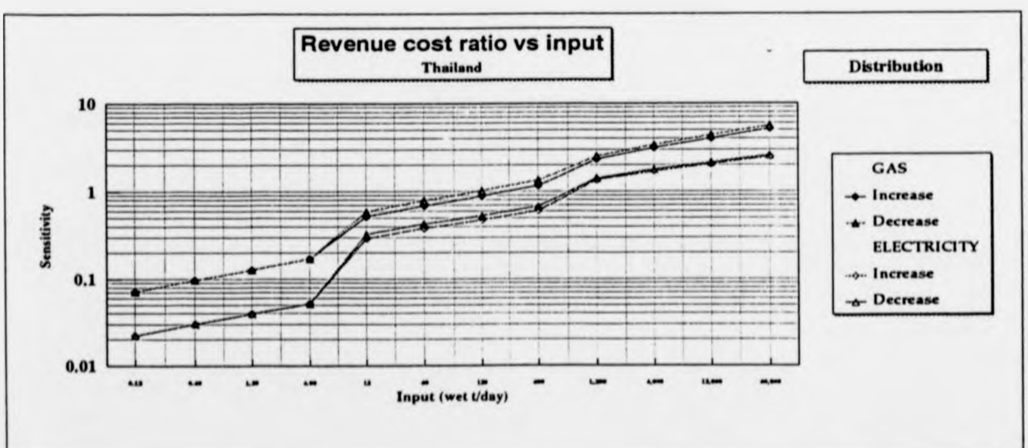
Varied parameter : Storage

		Percent change												
Bangladesh - gas production	Increase	100%	0.00	0.00	0.00	0.00	-0.10	-0.11	-0.11	-0.12	-0.09	-0.09	-0.09	-0.09
	Decrease	50%	0.00	0.00	0.00	0.00	0.12	0.13	0.14	0.14	0.10	0.10	0.11	0.11
Bangladesh - electricity production	Increase	100%	0.00	0.00	0.00	0.00	-0.08	-0.08	-0.08	-0.07	-0.05	-0.05	-0.05	-0.05
	Decrease	50%	0.00	0.00	0.00	0.00	0.09	0.09	0.09	0.08	0.06	0.06	0.05	0.05
Thailand - gas production	Increase	100%	0.00	0.00	0.00	0.00	-0.11	-0.11	-0.12	-0.12	-0.07	-0.07	-0.08	-0.08
	Decrease	50%	0.00	0.00	0.00	0.00	0.13	0.14	0.14	0.15	0.08	0.08	0.09	0.09
Thailand - electricity production	Increase	100%	0.00	0.00	0.00	0.00	-0.09	-0.09	-0.10	-0.10	-0.04	-0.04	-0.04	-0.04
	Decrease	50%	0.00	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.05	0.05	0.05	0.04

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Distribution*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREASE	%DECREASE
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	100%	50%			

REVENUE / COST RATIOS

Varied parameter : Distribution

Percentage variation **(Increase)** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.23	0.31	0.43	1.16	1.57	2.04	2.68	2.78	3.68	4.69	5.99
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.17	0.23	0.31	0.43	1.29	1.75	2.29	3.02	3.06	4.07	5.19	6.64
Bangladesh - electricity production	Increase	100%	0.05	0.07	0.09	0.12	0.59	0.75	0.93	1.16	1.51	1.87	2.23	2.69
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.09	0.12	0.63	0.81	1.01	1.25	1.59	1.97	2.35	2.82
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.17	0.52	0.69	0.89	1.16	2.34	3.13	4.01	5.18
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.59	0.80	1.03	1.35	2.54	3.40	4.38	5.65
Thailand - electricity production	Increase	100%	0.02	0.03	0.04	0.05	0.29	0.38	0.48	0.60	1.36	1.70	2.05	2.49
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.33	0.43	0.54	0.68	1.43	1.78	2.15	2.61

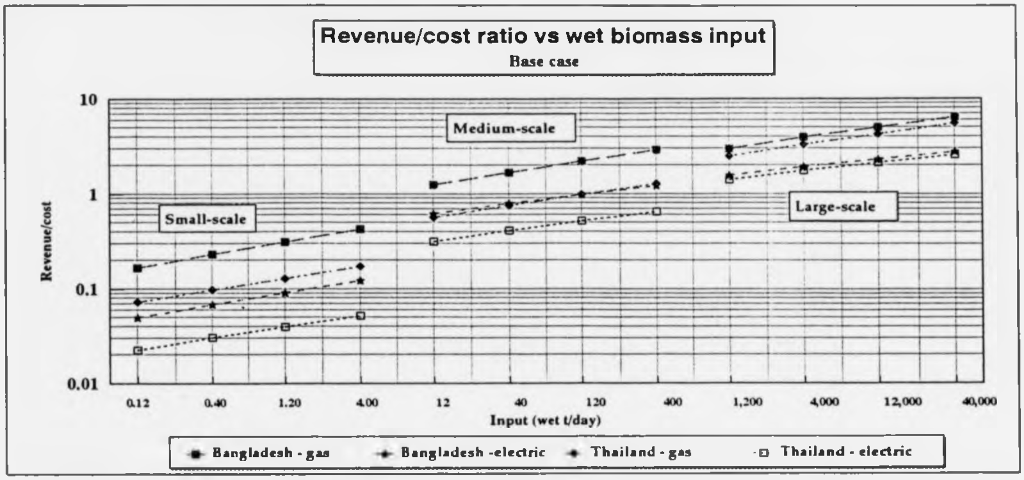
SENSITIVITY

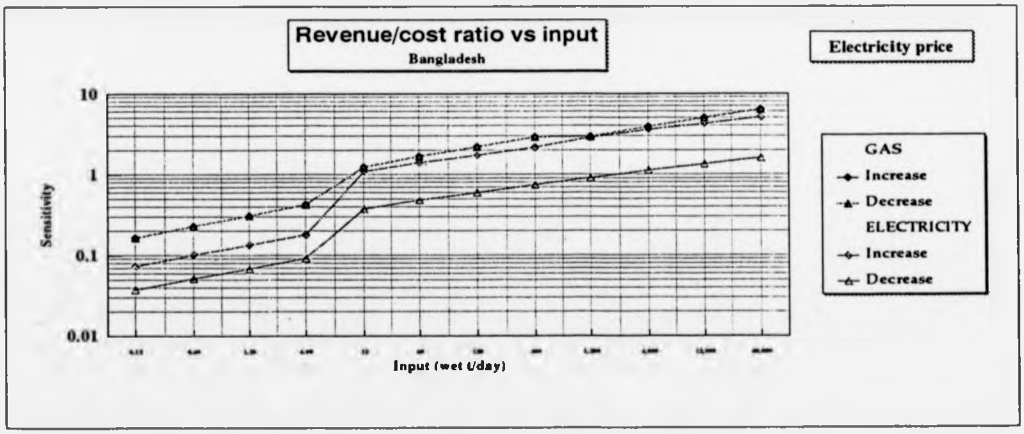
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

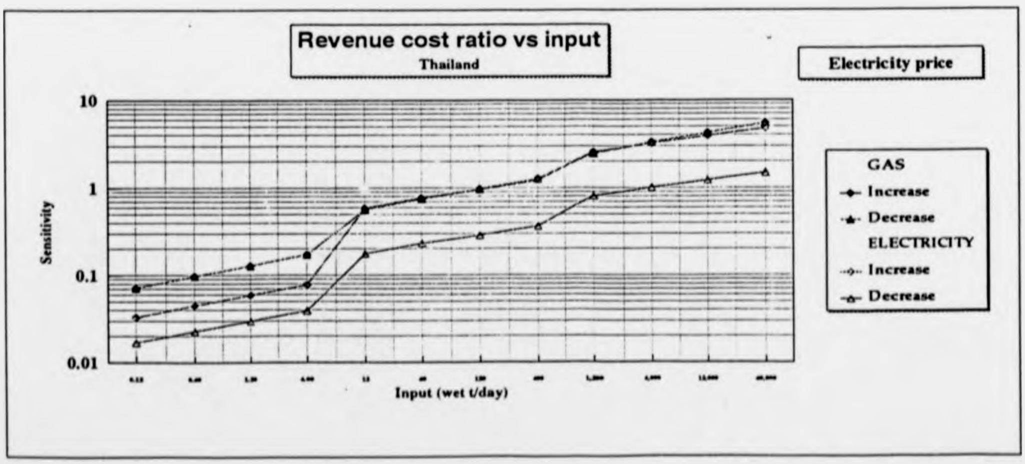
Varied parameter : Distribution

		Percent change												
Bangladesh - gas production	Increase	100%	0.00	0.00	0.00	0.00	-0.07	-0.07	-0.07	-0.08	-0.06	-0.06	-0.06	-0.07
	Decrease	50%	0.00	0.00	0.00	0.00	0.07	0.08	0.08	0.09	0.07	0.07	0.07	0.07
Bangladesh - electricity production	Increase	100%	0.00	0.00	0.00	0.00	-0.05	-0.05	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03
	Decrease	50%	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.03
Thailand - gas production	Increase	100%	0.00	0.00	0.00	0.00	-0.08	-0.09	-0.09	-0.09	-0.05	-0.05	-0.05	-0.06
	Decrease	50%	0.00	0.00	0.00	0.00	0.10	0.10	0.11	0.11	0.05	0.06	0.06	0.06
Thailand - electricity production	Increase	100%	0.00	0.00	0.00	0.00	-0.07	-0.07	-0.07	-0.07	-0.03	-0.03	-0.03	-0.03
	Decrease	50%	0.00	0.00	0.00	0.00	0.08	0.08	0.08	0.08	0.03	0.03	0.03	0.03

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Electricity price*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	% DECREA
1. Land rental	0%	0%	1. Electricity price	100%	50%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Electricity price

Percentage variation **(Increase** 100% **(Decrease)** 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
Bangladesh - electricity production	Increase	100%	0.07	0.10	0.13	0.18	1.10	1.41	1.74	2.17	2.88	3.56	4.26	5.11
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.04	0.05	0.07	0.09	0.38	0.48	0.60	0.75	0.91	1.12	1.34	1.61
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
Thailand - electricity production	Increase	100%	0.03	0.05	0.06	0.08	0.59	0.77	0.97	1.22	2.58	3.23	3.90	4.73
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.02	0.03	0.04	0.18	0.23	0.29	0.37	0.81	1.02	1.23	1.49

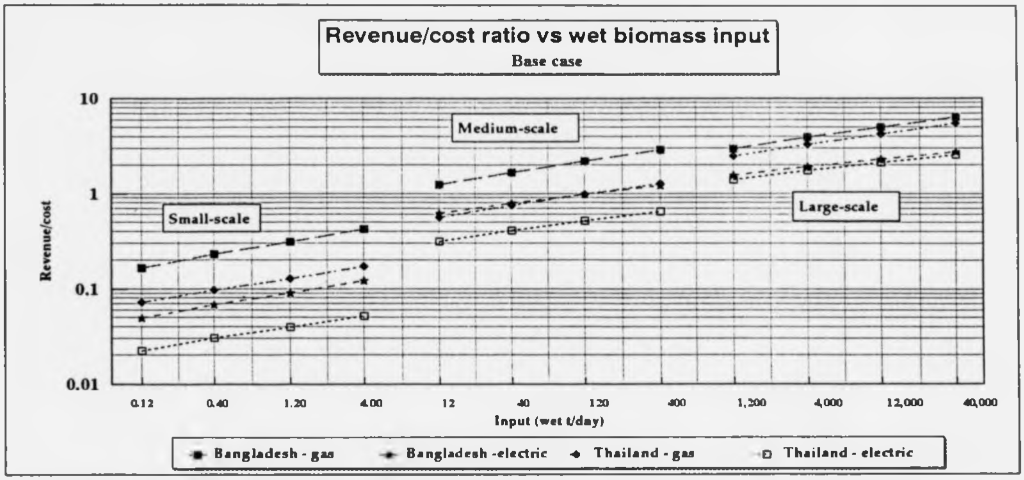
SENSITIVITY

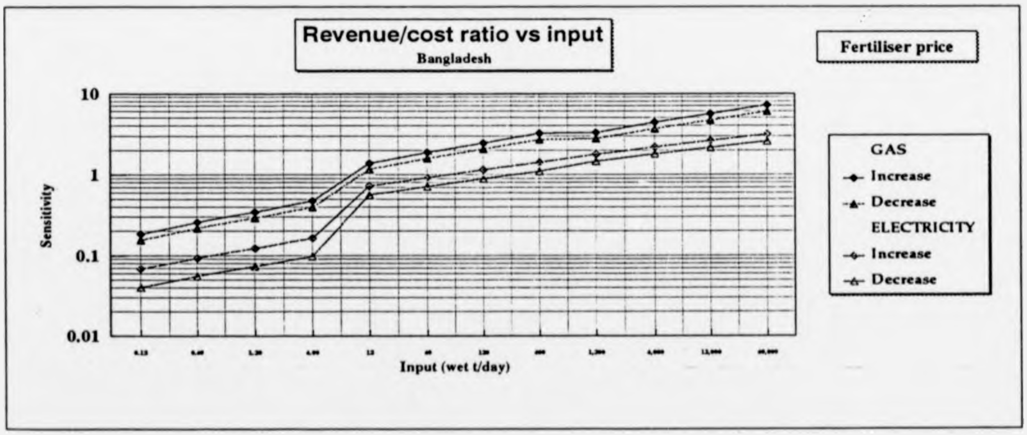
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

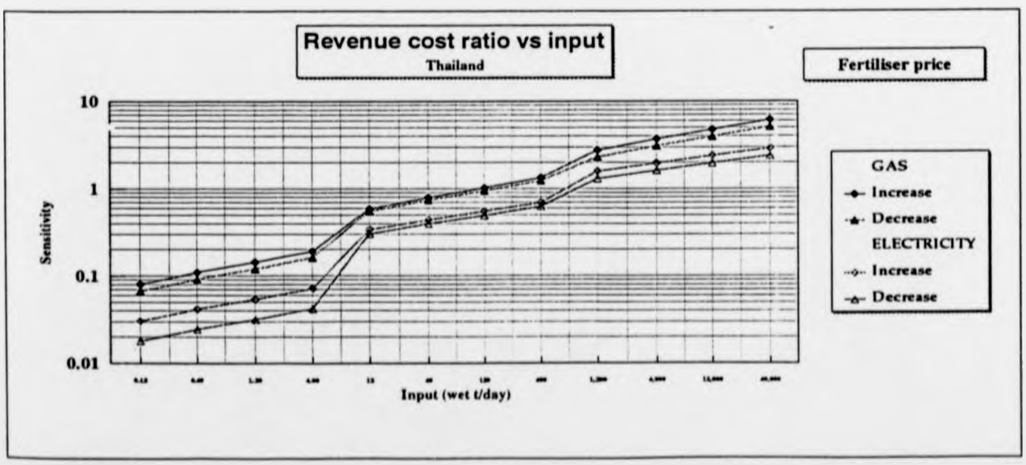
Varied parameter : Electricity price

		Percent change												
Bangladesh - gas production	Increase	100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Decrease	50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bangladesh - electricity production	Increase	100%	0.49	0.49	0.49	0.49	0.78	0.78	0.78	0.78	0.84	0.84	0.84	0.84
	Decrease	50%	-0.49	-0.49	-0.49	-0.49	-0.78	-0.78	-0.78	-0.78	-0.84	-0.84	-0.84	-0.84
Thailand - gas production	Increase	100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Decrease	50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thailand - electricity production	Increase	100%	0.49	0.49	0.49	0.49	0.88	0.88	0.88	0.88	0.84	0.84	0.84	0.84
	Decrease	50%	-0.49	-0.49	-0.49	-0.49	-0.88	-0.88	-0.88	-0.88	-0.84	-0.84	-0.84	-0.84

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2 Labour rates	0%	2. Gas price	0%
3 Capital costs	0%	3. Fertiliser price	0%
4 Cost of growth	0%	4. Fibre price	0%
5 Cost of harvesting	0%		
6 Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8 Cost of storage	0%		
9 Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Fertiliser price*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREA
1. Land rental	0%	0%	1. Electricity price	0%	0%
2 Labour rates	0%	0%	2. Gas price	0%	0%
3 Capital costs	0%	0%	3 Fertiliser price	100%	50%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Fertiliser price

Percentage variation **(Increase** 100% **(Decrease)** 50%

			Wet input (t/d) 0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.19	0.26	0.35	0.48	1.40	1.89	2.47	3.25	3.32	4.42	5.63	7.20
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.16	0.22	0.29	0.40	1.17	1.58	2.06	2.72	2.78	3.69	4.70	6.02
Bangladesh - electricity production	Increase	100%	0.07	0.09	0.12	0.17	0.73	0.93	1.15	1.43	1.78	2.19	2.63	3.15
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.04	0.06	0.07	0.10	0.56	0.72	0.89	1.11	1.46	1.80	2.16	2.59
Thailand - gas production	Increase	100%	0.08	0.11	0.14	0.19	0.59	0.79	1.03	1.34	2.77	3.71	4.77	6.16
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.09	0.12	0.16	0.55	0.74	0.96	1.25	2.32	3.10	3.99	5.15
Thailand - electricity production	Increase	100%	0.03	0.04	0.05	0.07	0.34	0.44	0.55	0.70	1.59	1.99	2.40	2.91
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.02	0.03	0.04	0.30	0.40	0.50	0.63	1.31	1.63	1.98	2.39

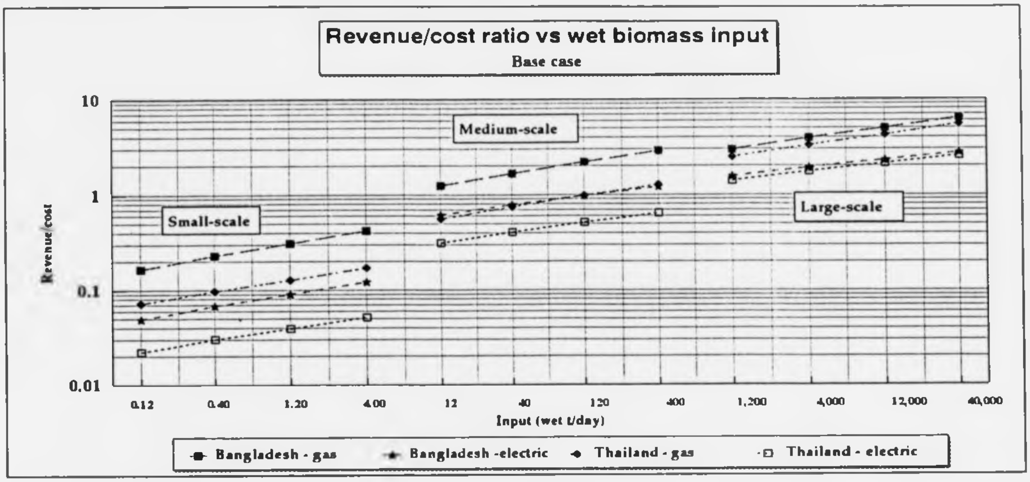
SENSITIVITY

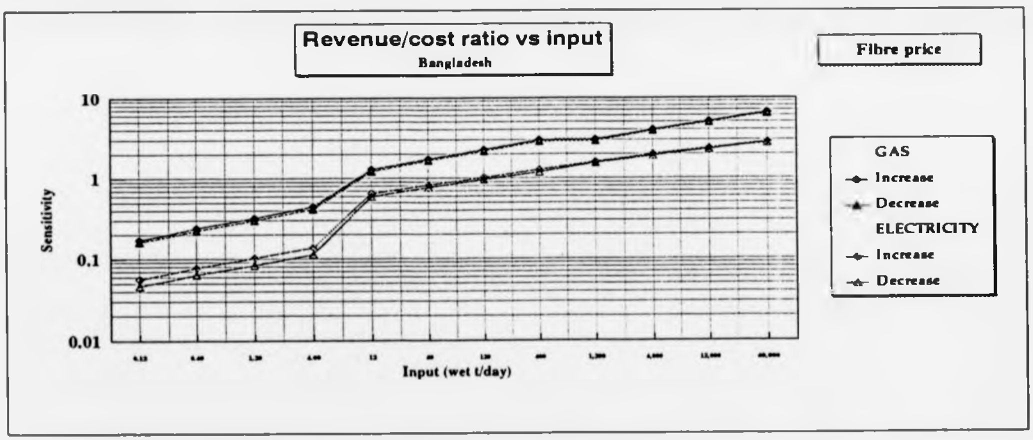
$\frac{\text{New ratio - old ratio}}{\text{Old ratio}}$ divided by $\frac{\text{New sub-item - old sub-item}}{\text{old sub-item}}$

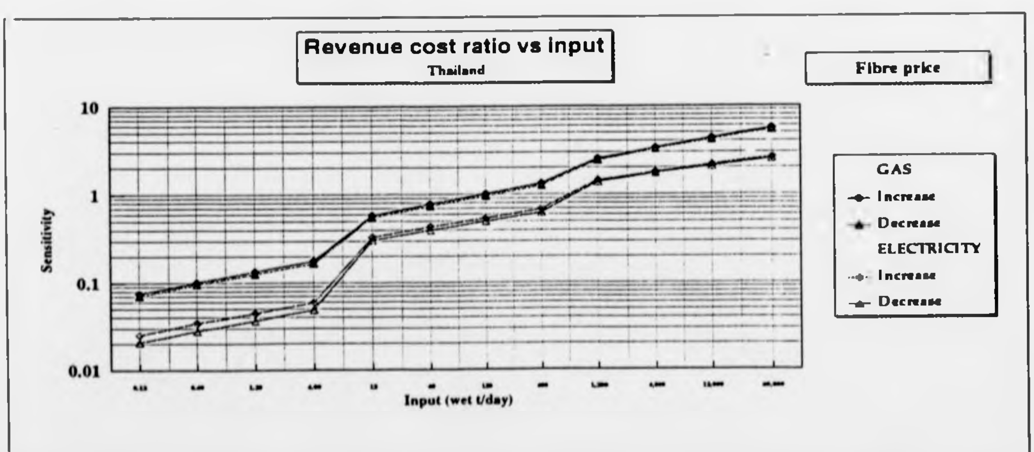
Varied parameter : Fertiliser price

		Percent change												
Bangladesh - gas production	Increase	100%	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	Decrease	50%	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
Bangladesh - electricity production	Increase	100%	0.38	0.38	0.38	0.38	0.18	0.18	0.18	0.18	0.13	0.13	0.13	0.13
	Decrease	50%	-0.38	-0.38	-0.38	-0.38	-0.18	-0.18	-0.18	-0.18	-0.13	-0.13	-0.13	-0.13
Thailand - gas production	Increase	100%	0.12	0.12	0.12	0.12	0.05	0.05	0.05	0.05	0.12	0.12	0.12	0.12
	Decrease	50%	-0.12	-0.12	-0.12	-0.12	-0.05	-0.05	-0.05	-0.05	-0.12	-0.12	-0.12	-0.12
Thailand - electricity production	Increase	100%	0.38	0.38	0.38	0.38	0.07	0.07	0.07	0.07	0.13	0.13	0.13	0.13
	Decrease	50%	-0.38	-0.38	-0.38	-0.38	-0.07	-0.07	-0.07	-0.07	-0.13	-0.13	-0.13	-0.13

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Fibre price*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREAS	%DECREAS
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	0%	0%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	100%	50%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Fibre price
Percentage variation **(Increas** 100%
(Decrease) 50%

			Wet input (t/d) 0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.17	0.24	0.32	0.44	1.29	1.74	2.27	3.00	3.02	4.02	5.12	6.55
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.16	0.23	0.30	0.42	1.22	1.66	2.16	2.85	2.93	3.89	4.96	6.34
Bangladesh - electricity production	Increase	100%	0.06	0.08	0.10	0.14	0.65	0.83	1.03	1.28	1.60	1.98	2.37	2.84
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.06	0.08	0.11	0.60	0.77	0.96	1.19	1.55	1.91	2.29	2.74
Thailand - gas production	Increase	100%	0.07	0.10	0.13	0.18	0.58	0.79	1.02	1.33	2.52	3.38	4.34	5.60
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.07	0.10	0.13	0.17	0.55	0.74	0.96	1.26	2.44	3.27	4.20	5.42
Thailand - electricity production	Increase	100%	0.03	0.03	0.04	0.06	0.33	0.43	0.54	0.69	1.44	1.80	2.17	2.63
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.31	0.40	0.50	0.63	1.39	1.73	2.09	2.54

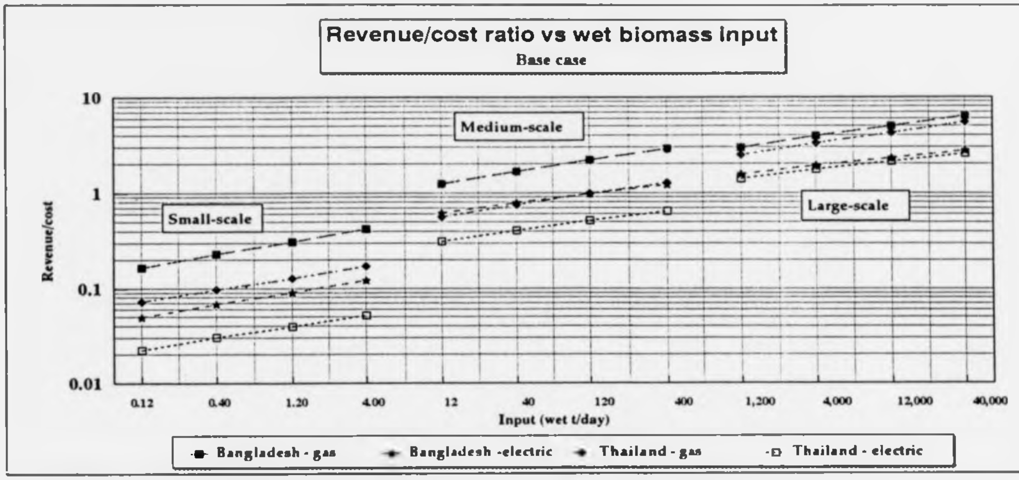
SENSITIVITY

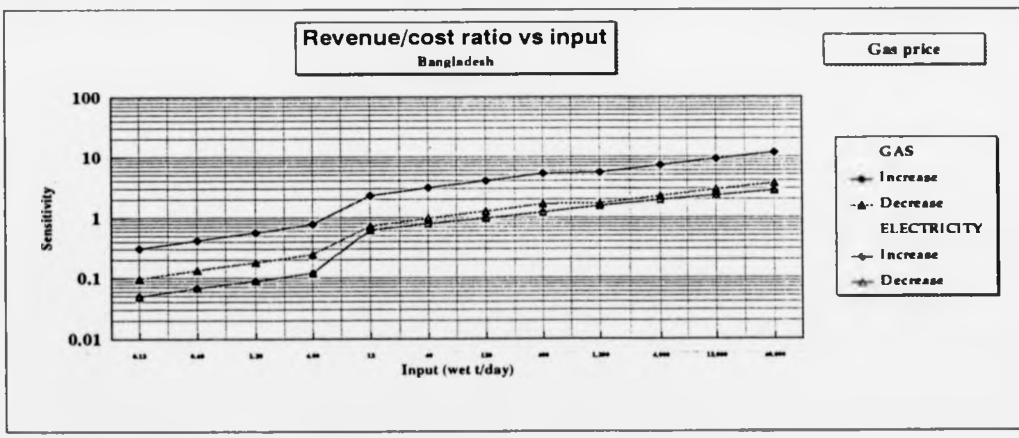
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

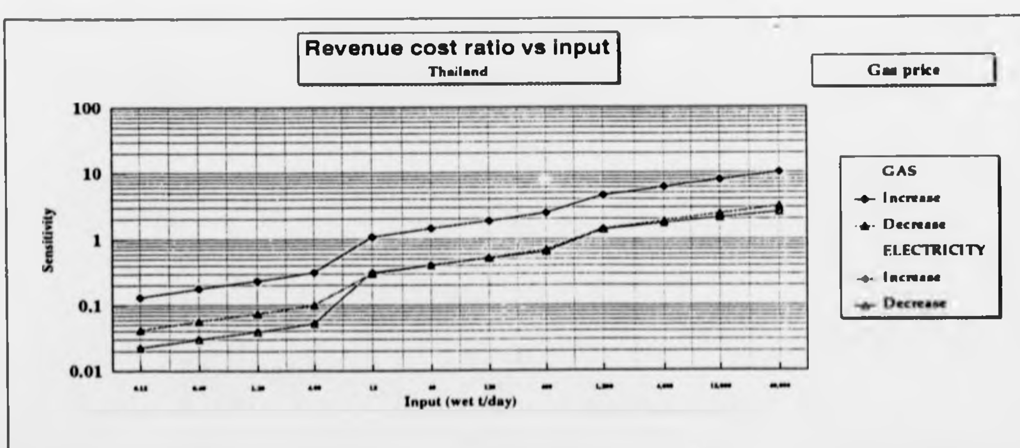
Varied parameter : Fibre price

		Percent change												
Bangladesh - gas production	Increase	100%	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
	Decrease	50%	-0.04	-0.04	-0.04	-0.04	-0.03	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02	-0.02
Bangladesh - electricity production	Increase	100%	0.13	0.13	0.13	0.13	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02
	Decrease	50%	-0.13	-0.13	-0.13	-0.13	-0.05	-0.05	-0.05	-0.05	-0.02	-0.02	-0.02	-0.02
Thailand - gas production	Increase	100%	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02
	Decrease	50%	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.02	-0.02	-0.02	-0.02
Thailand - electricity production	Increase	100%	0.13	0.13	0.13	0.13	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02
	Decrease	50%	-0.13	-0.13	-0.13	-0.13	-0.05	-0.05	-0.05	-0.05	-0.02	-0.02	-0.02	-0.02

REVENUE/ COST RATIO ANALYSIS







BASE-CASE VARIATIONS

Varied parameter: *Base case*

INPUTS	% CHANGE	OUTPUTS	% CHANGE
1. Land rental	0%	1. Electricity price	0%
2. Labour rates	0%	2. Gas price	0%
3. Capital costs	0%	3. Fertiliser price	0%
4. Cost of growth	0%	4. Fibre price	0%
5. Cost of harvesting	0%		
6. Cost of pre-treatment	0%		
7. Cost of digestion	0%		
8. Cost of storage	0%		
9. Cost of distribution	0%		

HIGH/LOW SENSITIVITY CASE VARIATIONS

Varied parameter : *Gas price*

INPUTS	%INCREASE	%DECREASE	OUTPUTS	% INCREA	%DECREA
1. Land rental	0%	0%	1. Electricity price	0%	0%
2. Labour rates	0%	0%	2. Gas price	100%	50%
3. Capital costs	0%	0%	3. Fertiliser price	0%	0%
4. Cost of growth	0%	0%	4. Fibre price	0%	0%
5. Cost of harvesting	0%	0%			
6. Cost of pre-treatment	0%	0%			
7. Cost of digestion	0%	0%			
8. Cost of storage	0%	0%			
9. Cost of distribution	0%	0%			

REVENUE / COST RATIOS

Varied parameter : Gas price
Percentage variation **(Increase** 100%
(Decrease) 50%

Wet input (t/d)

			0.12	0.4	1.2	4	12	40	120	400	1,200	4,000	12,000	40,000
Bangladesh - gas production	Increase	100%	0.31	0.42	0.57	0.78	2.30	3.11	4.06	5.35	5.49	7.29	9.30	11.89
	Base case	0%	0.17	0.23	0.31	0.43	1.24	1.69	2.20	2.90	2.96	3.93	5.01	6.41
	Decrease	50%	0.10	0.13	0.18	0.25	0.72	0.97	1.27	1.67	1.69	2.25	2.87	3.67
Bangladesh - electricity production	Increase	100%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Base case	0%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
	Decrease	50%	0.05	0.07	0.09	0.12	0.62	0.79	0.98	1.22	1.56	1.93	2.31	2.77
Thailand - gas production	Increase	100%	0.13	0.18	0.24	0.31	1.08	1.45	1.88	2.46	4.58	6.13	7.88	10.17
	Base case	0%	0.07	0.10	0.13	0.17	0.56	0.76	0.98	1.28	2.47	3.31	4.25	5.48
	Decrease	50%	0.04	0.06	0.07	0.10	0.31	0.41	0.53	0.69	1.41	1.89	2.43	3.14
Thailand - electricity production	Increase	100%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Base case	0%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57
	Decrease	50%	0.02	0.03	0.04	0.05	0.32	0.41	0.52	0.65	1.40	1.75	2.12	2.57

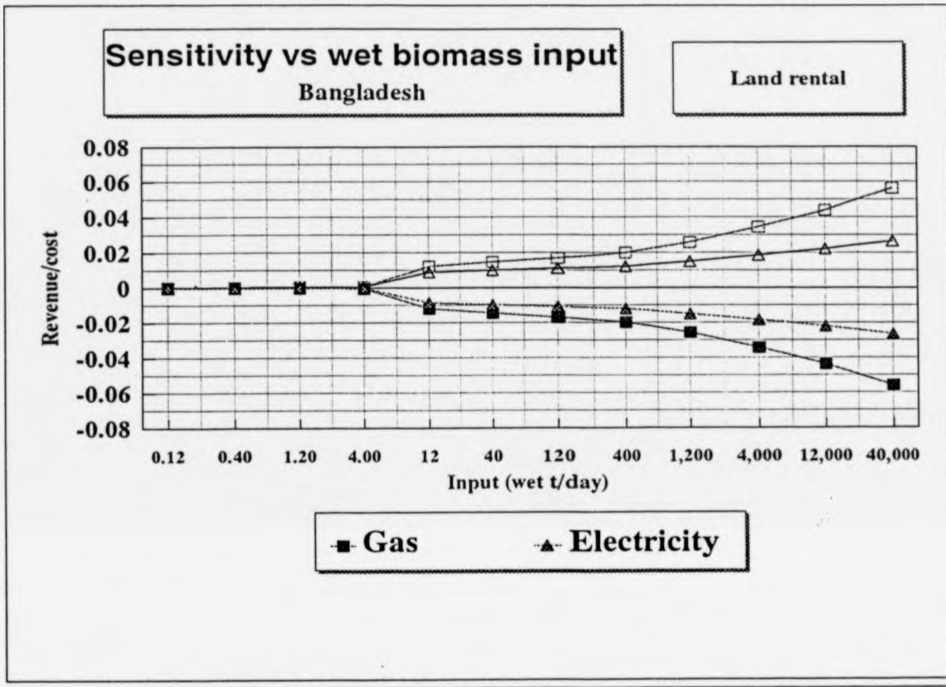
SENSITIVITY

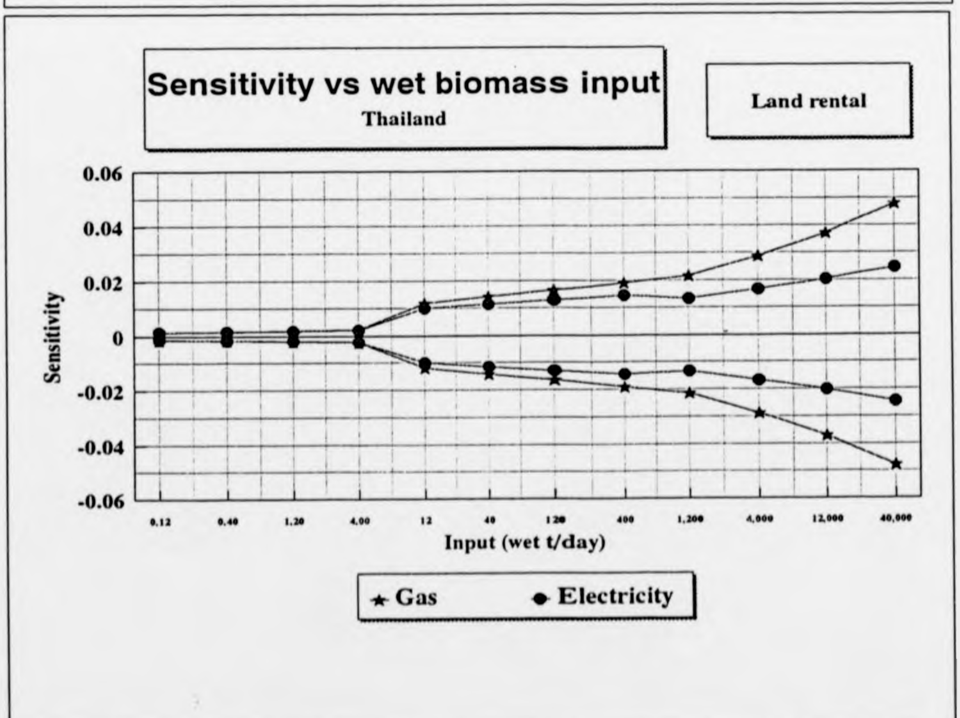
New ratio - old ratio / Old ratio divided by New sub-item - old sub-item / old sub-item

Varied parameter : Gas price

		Percent change												
Bangladesh - gas production	Increase	100%	0.84	0.84	0.84	0.84	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Decrease	50%	-0.84	-0.84	-0.84	-0.84	-0.85	-0.85	-0.85	-0.85	-0.85	-0.85	-0.85	-0.85
Bangladesh - electricity production	Increase	100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Decrease	50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thailand - gas production	Increase	100%	0.84	0.84	0.84	0.84	0.92	0.92	0.92	0.92	0.85	0.85	0.85	0.85
	Decrease	50%	-0.84	-0.84	-0.84	-0.84	-0.92	-0.92	-0.92	-0.92	-0.85	-0.85	-0.85	-0.85
Thailand - electricity production	Increase	100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Decrease	50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SENSITIVITY ANALYSIS





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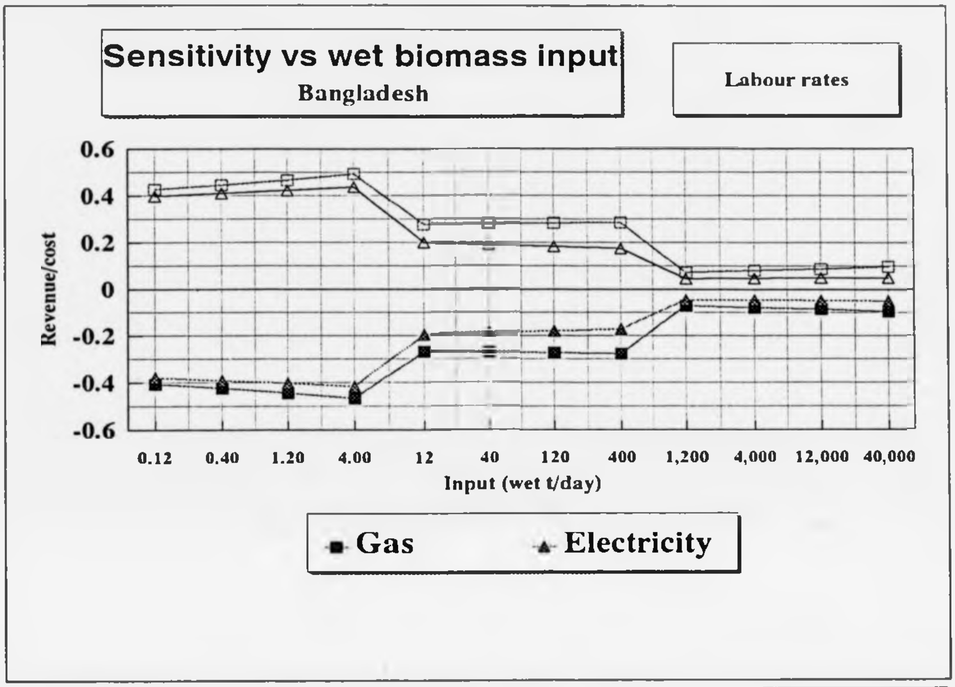

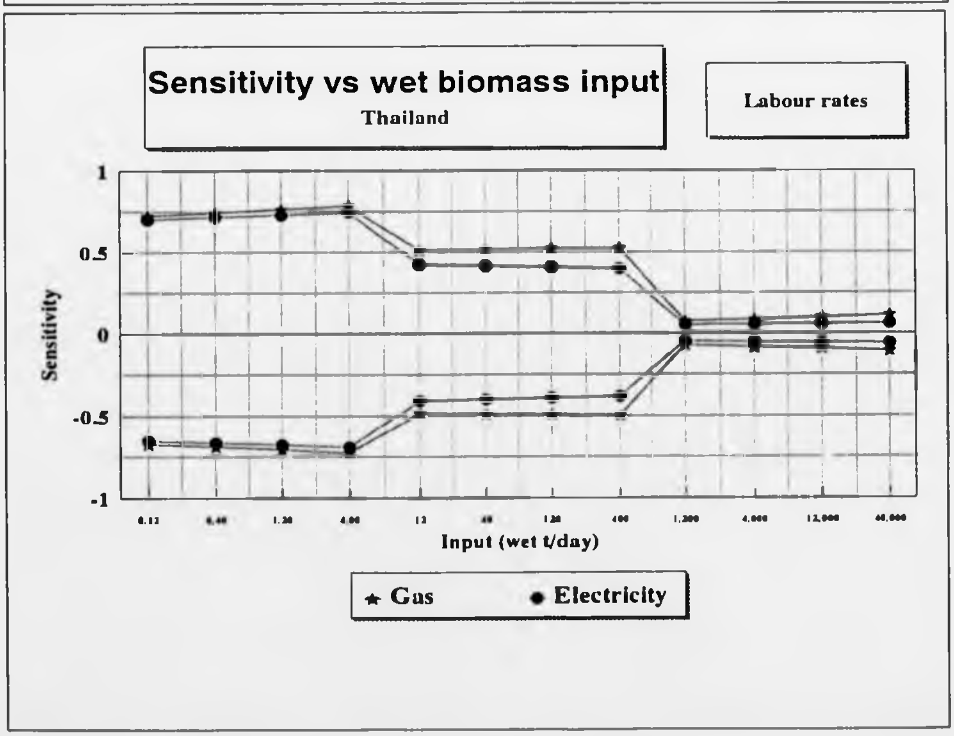

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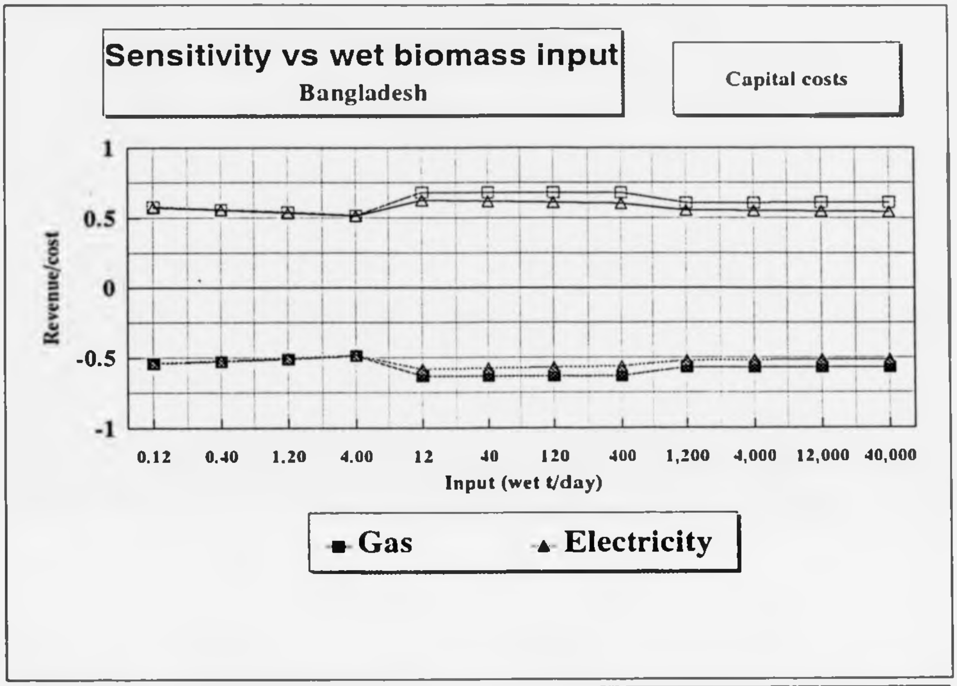

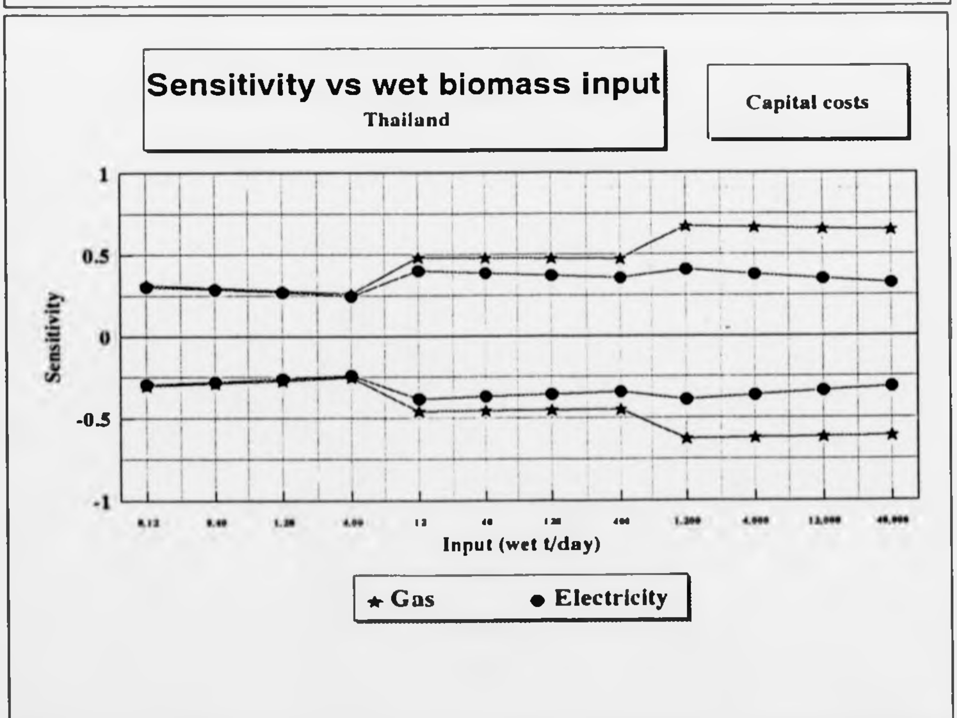

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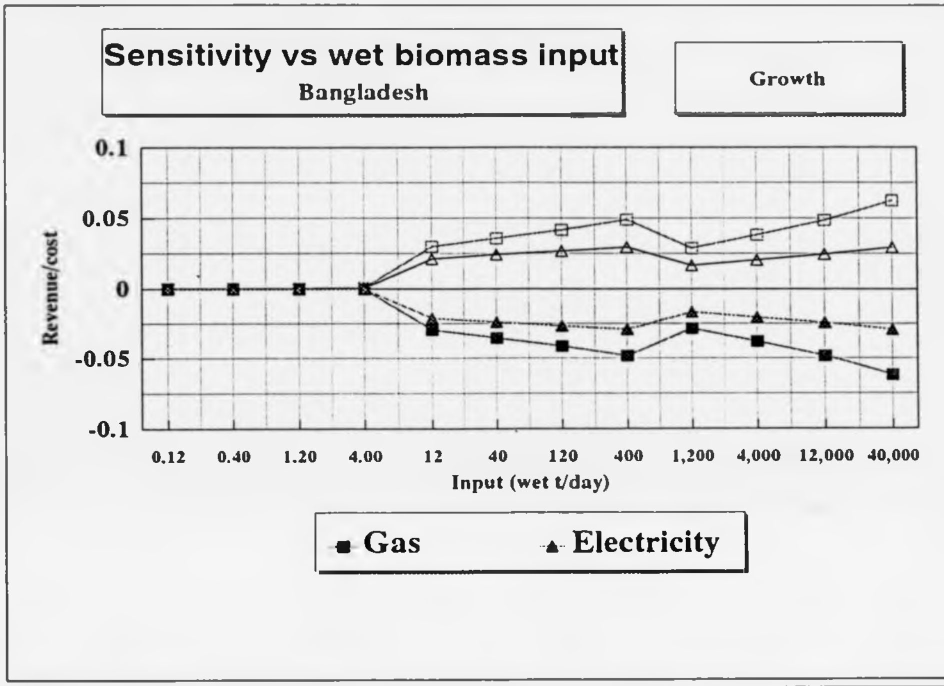

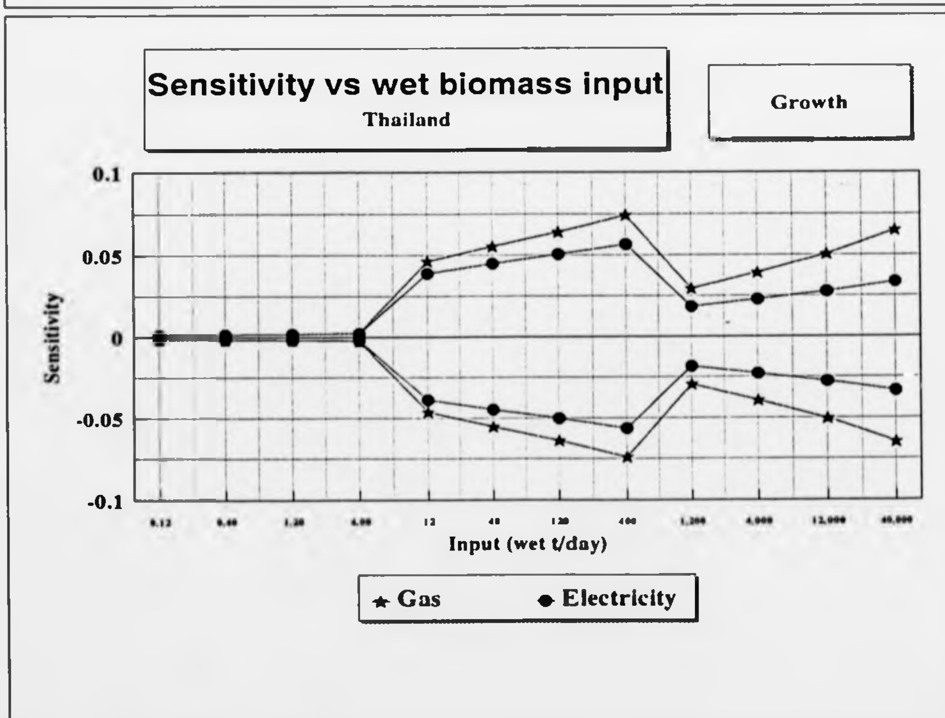

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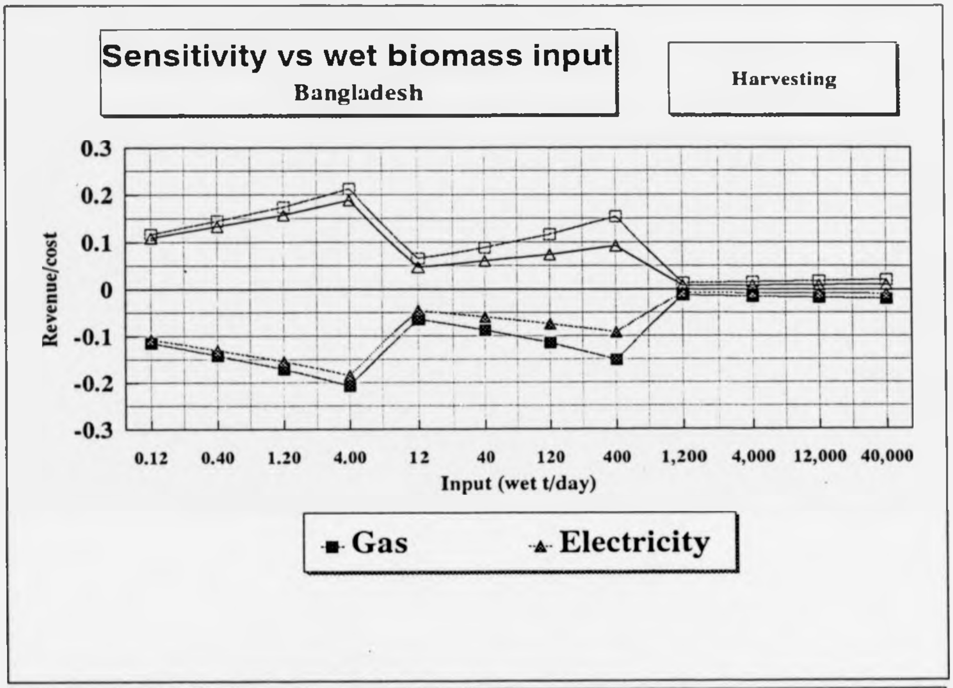

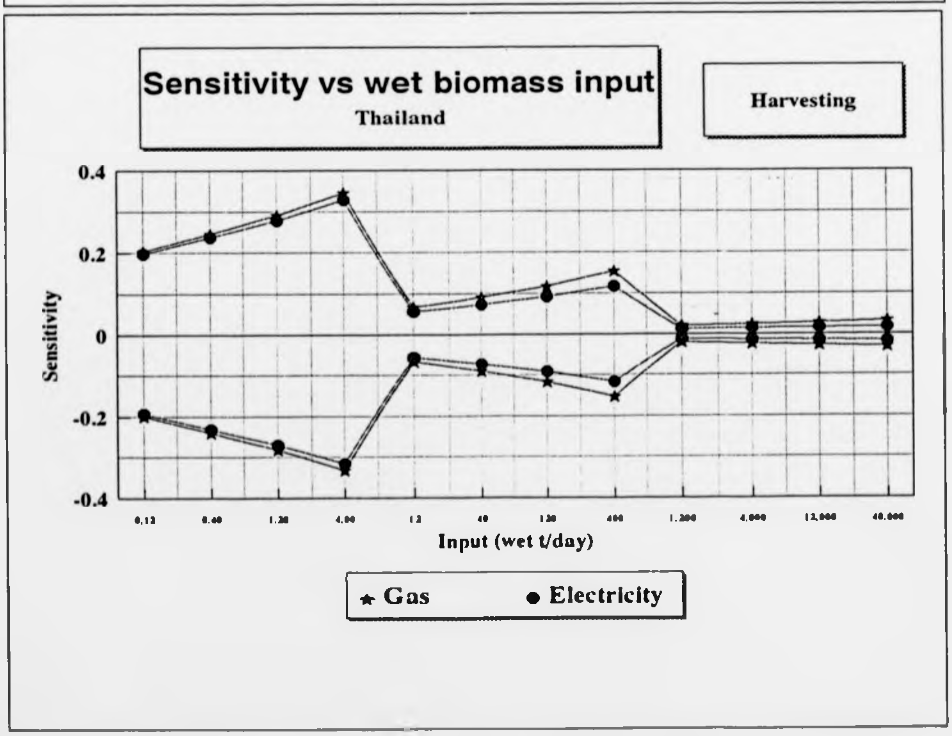

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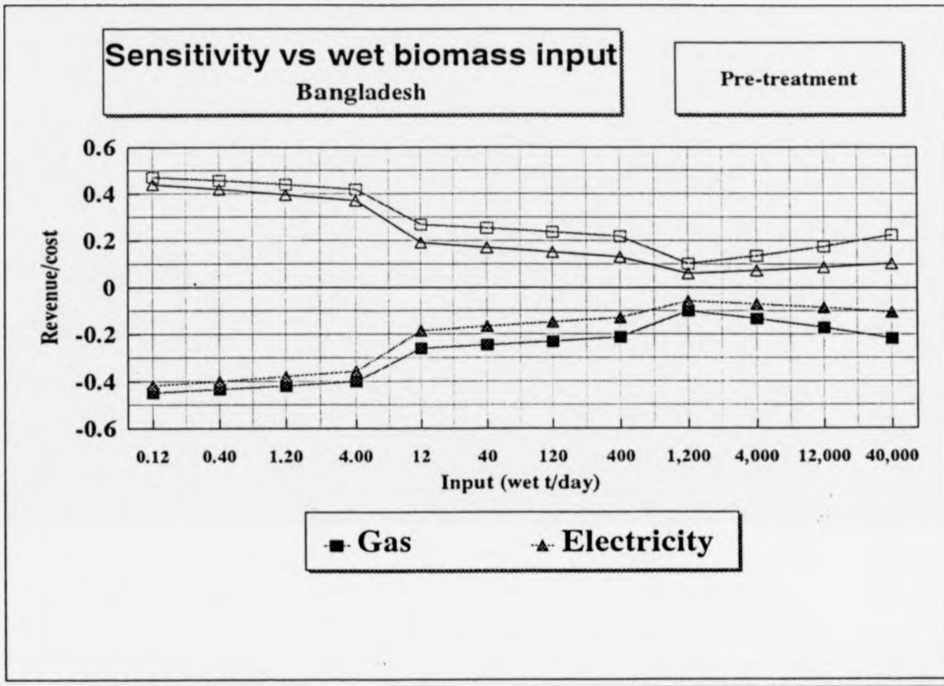

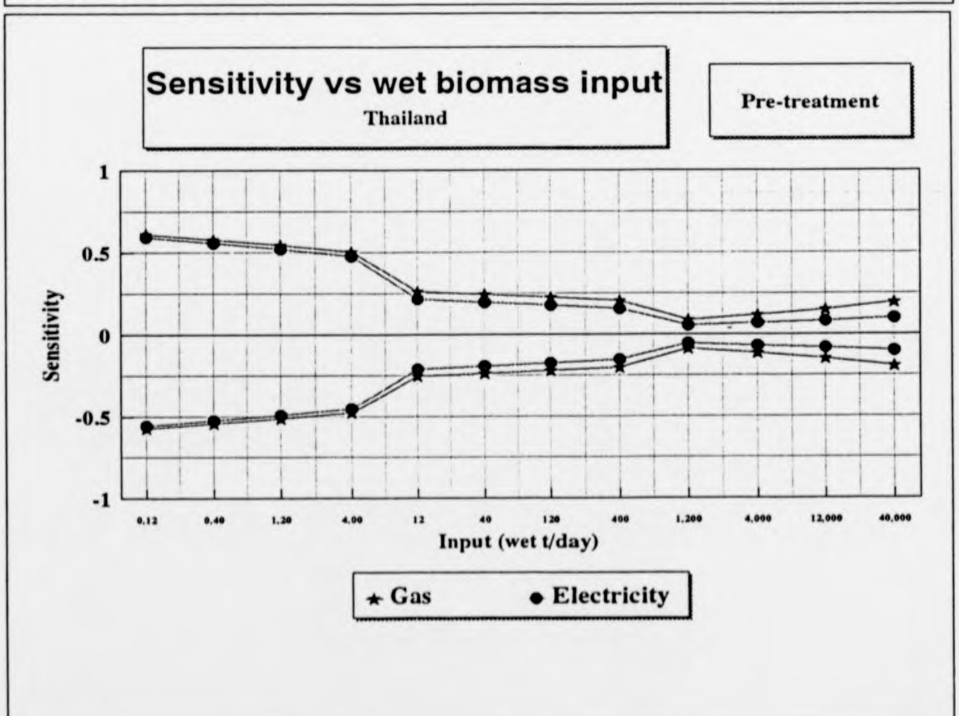

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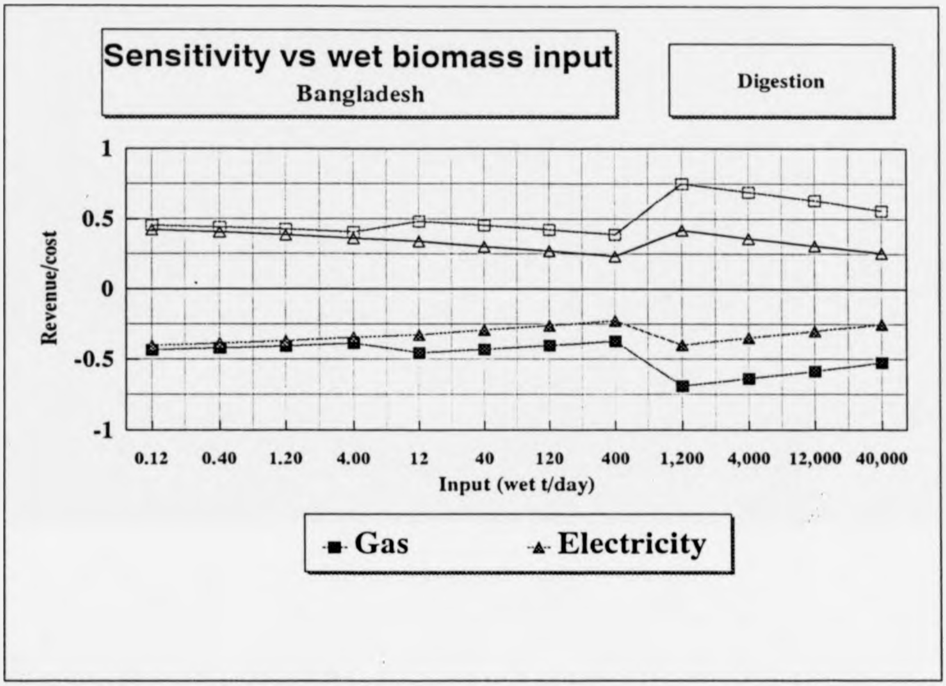

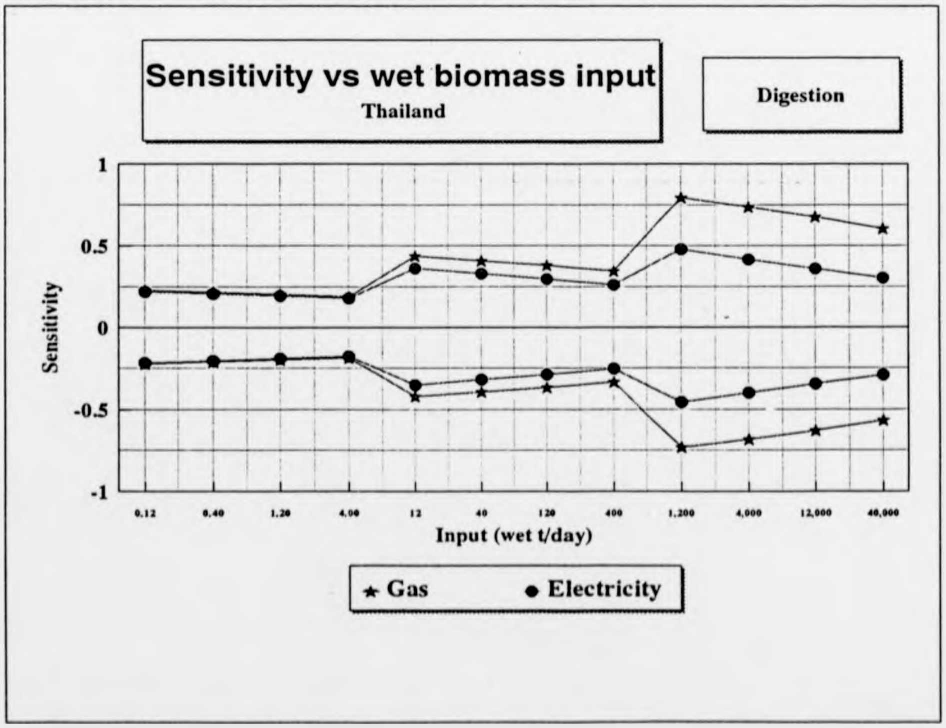

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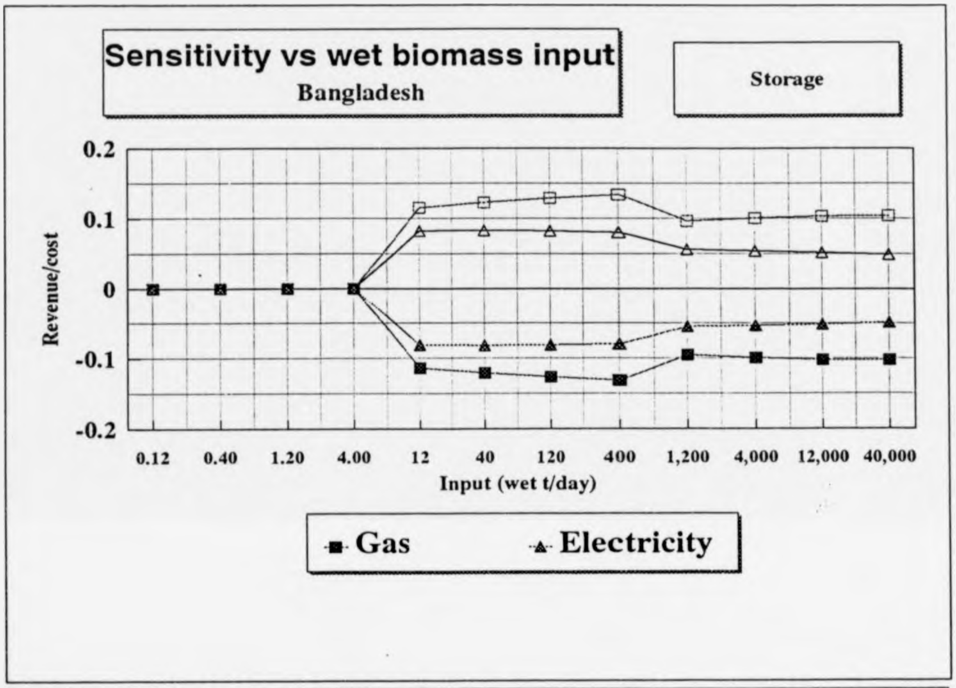

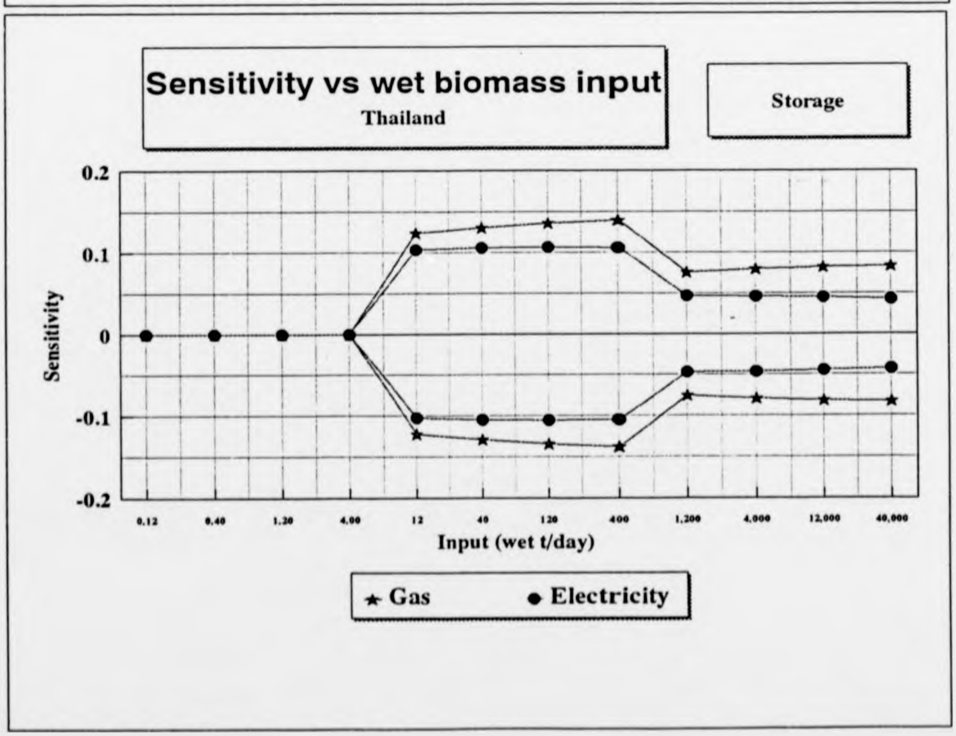

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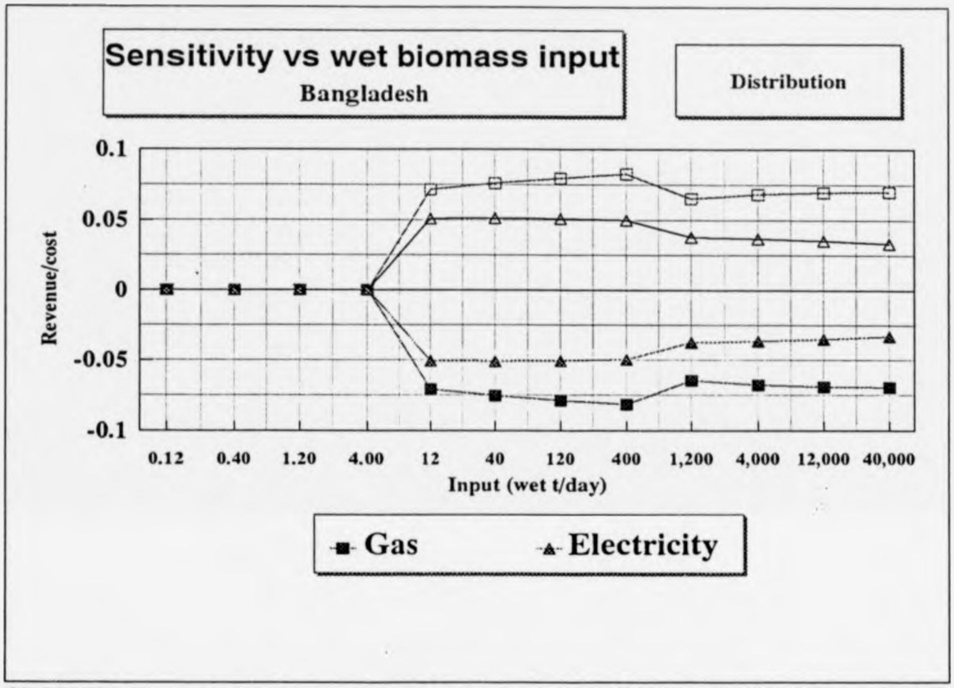

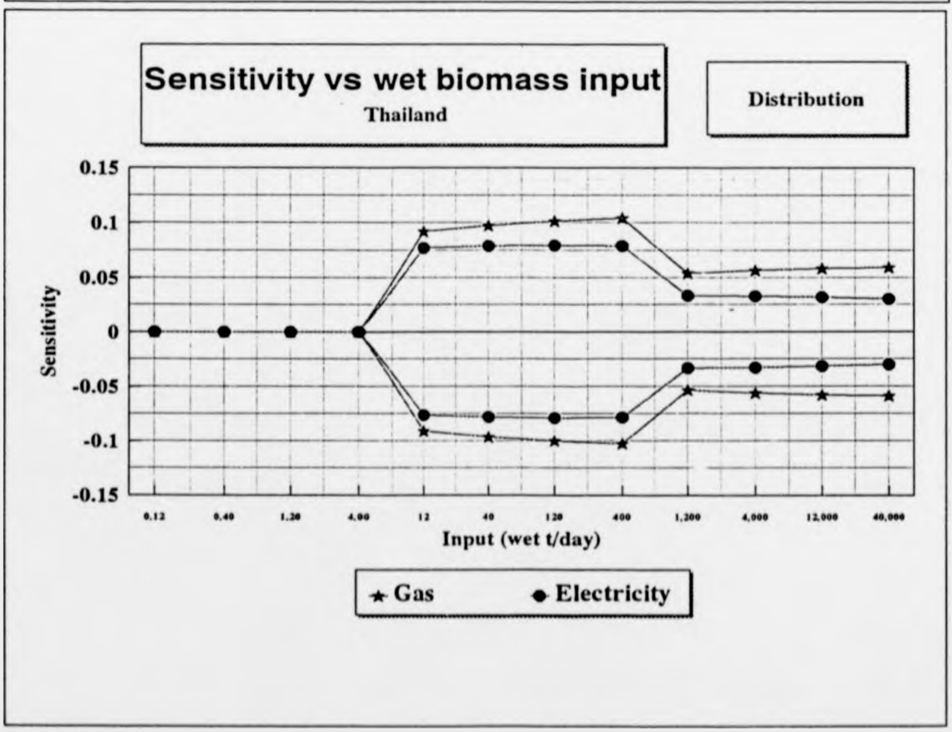

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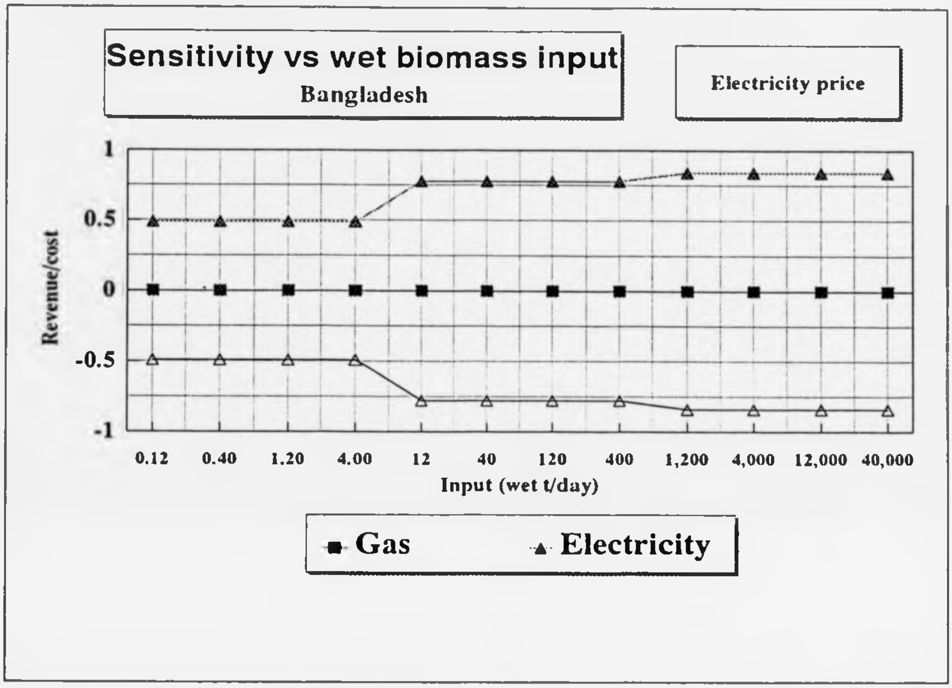

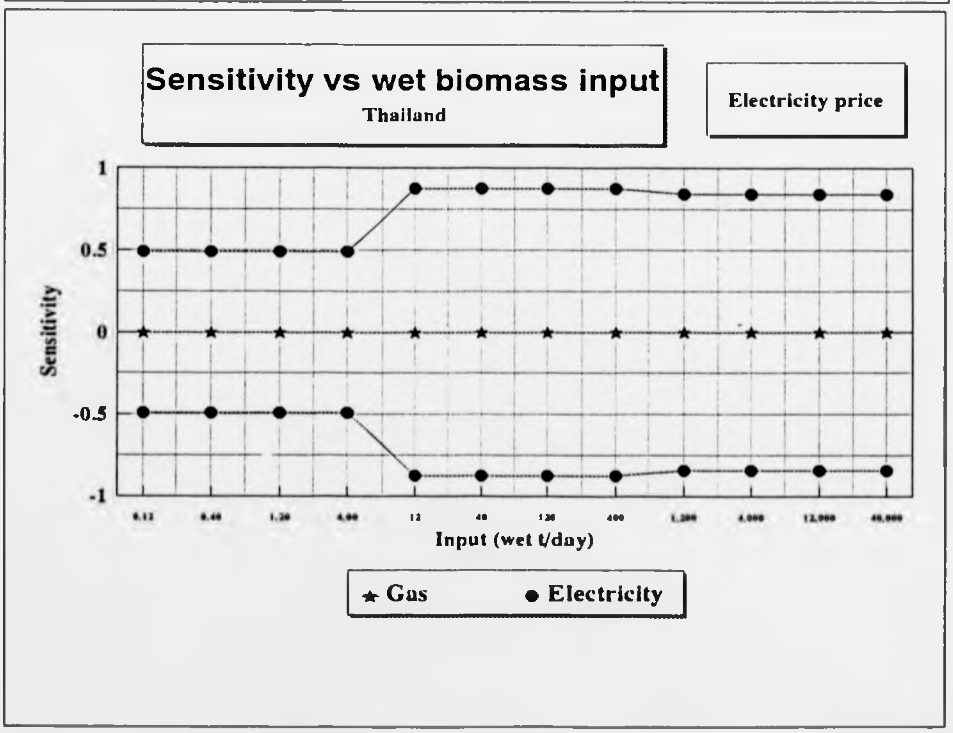

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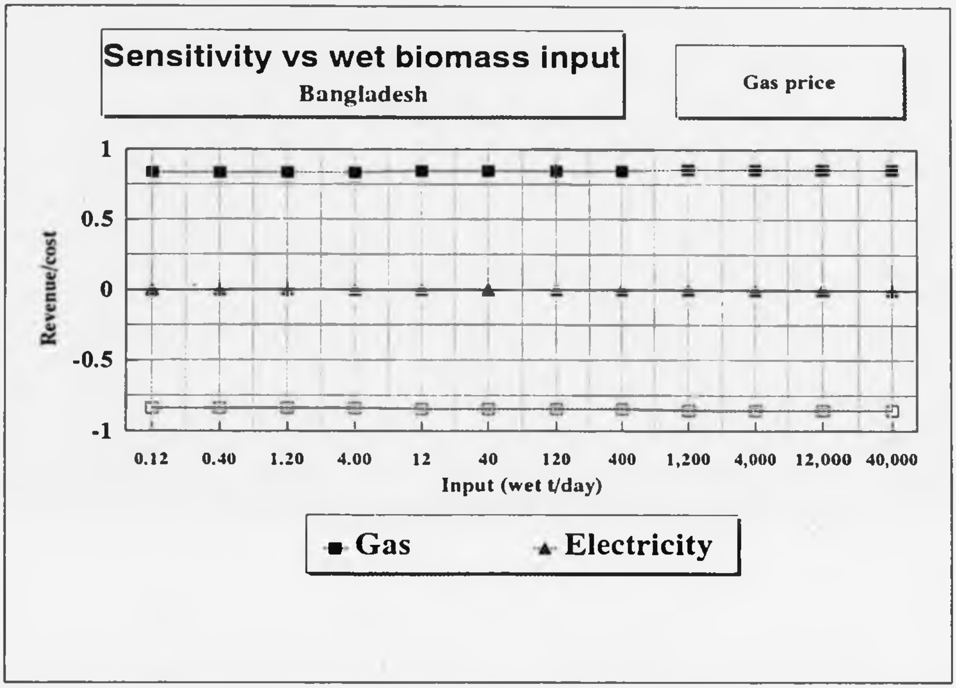

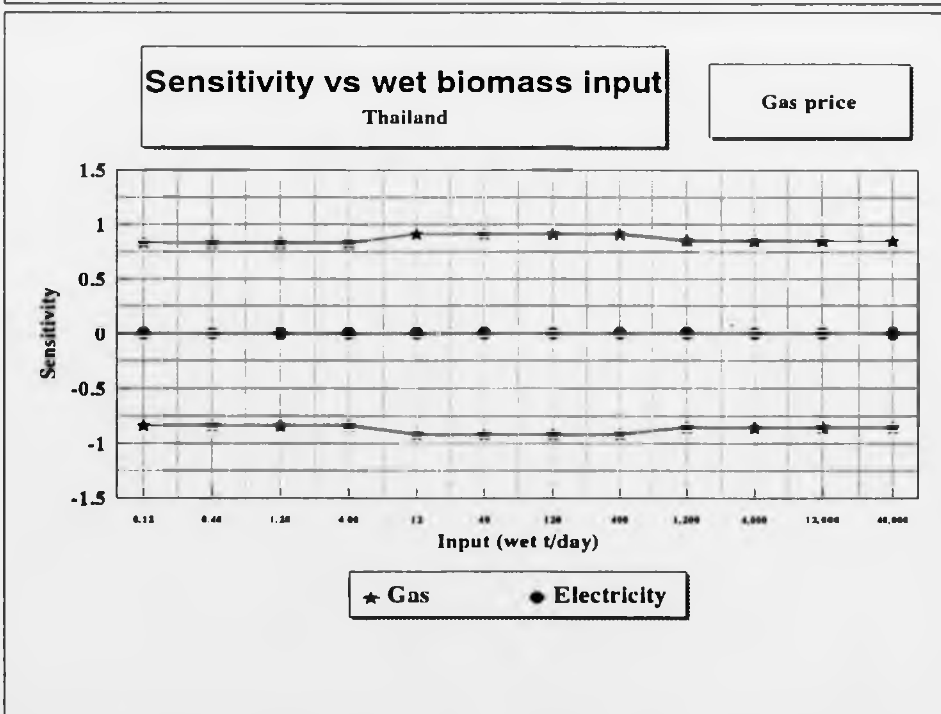

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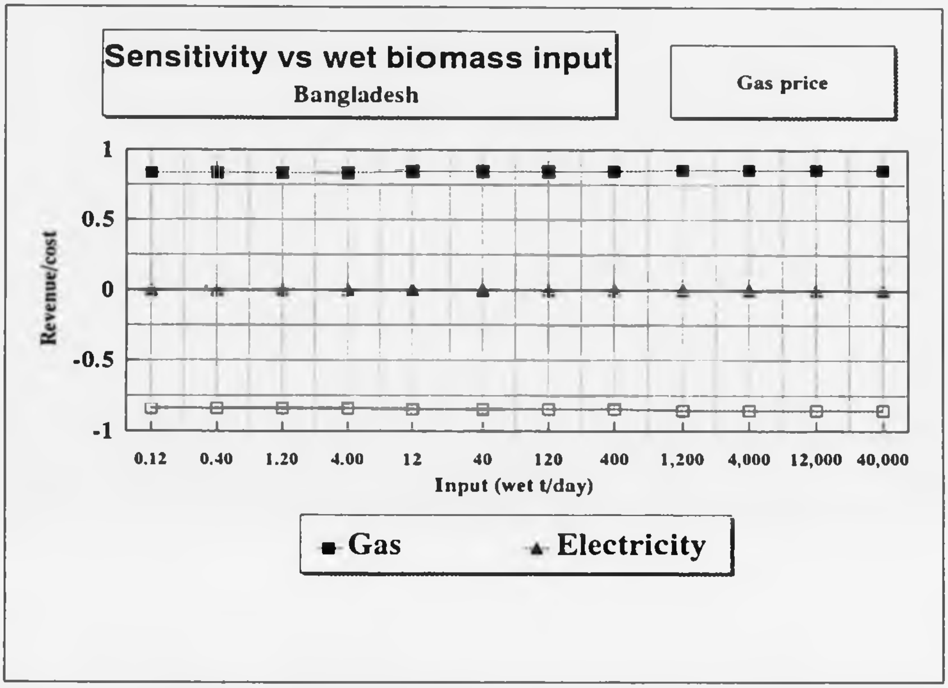

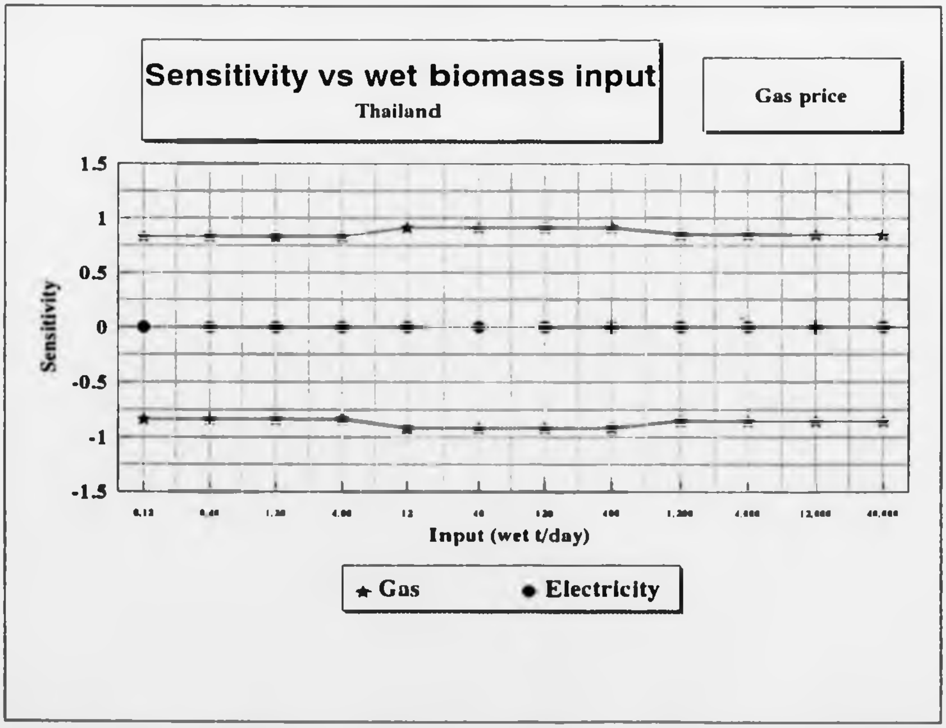

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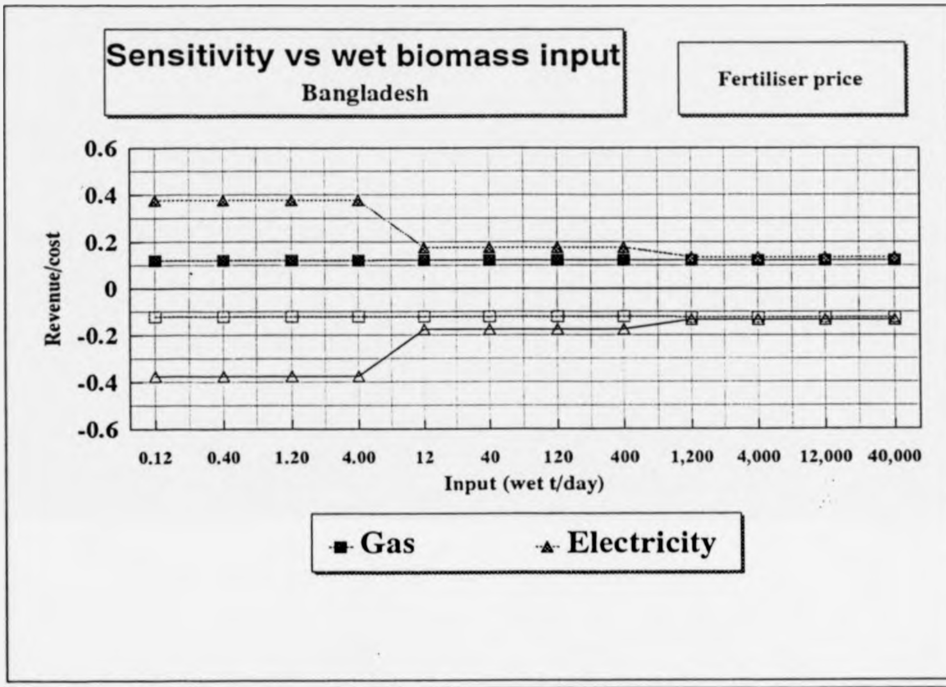

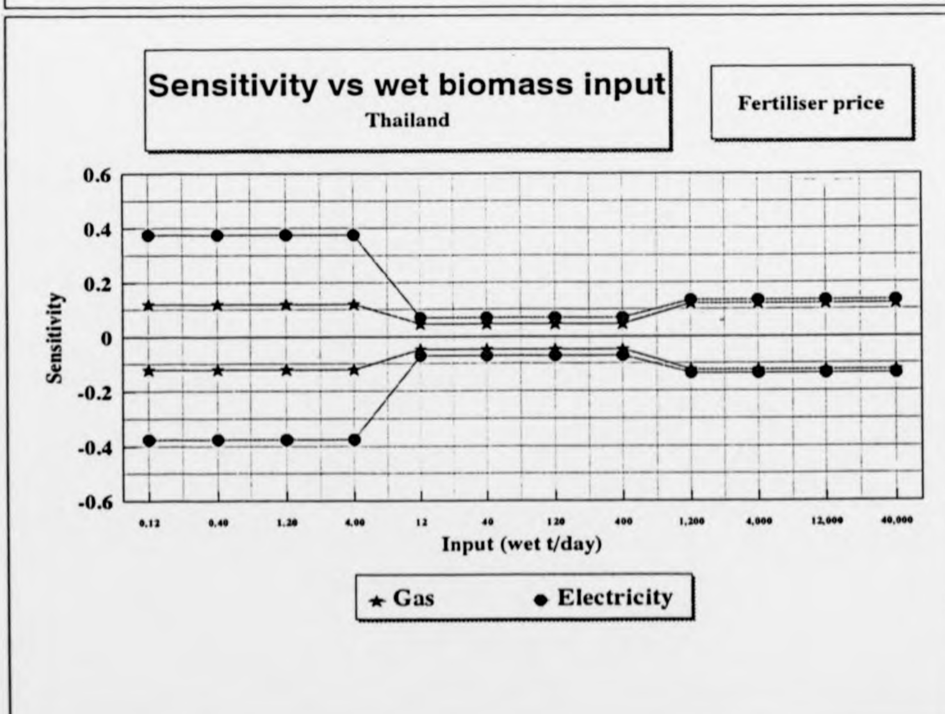

SENSITIVITY ANALYSIS