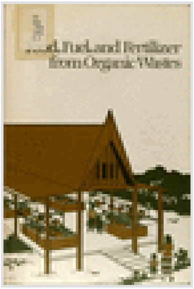

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Panel on Food, Fuel, and Fertilizer from Organic Wastes

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Preface

This report examines some of the opportunities for the utilization of organic wastes and residues commonly found in the poorer rural areas of the world. It is based on discussions and presentations at a panel meeting of the Advisory Committee on Technology Innovation held on 6-8 August, 1979, in Airlie, Virginia, USA.

The purpose is to set forth an array of alternatives for possible application where existing waste usage (or nonusage) is no longer appropriate.

The processes described range from simple and inexpensive techniques to those more complex and costly. Many are already in use in rural areas, but some are still being developed at universities and research institutes. Although there are some generalizations on economic factors, projections of operating and capital costs in vastly different environments are impossible. Most of the processes described are both labor intensive and site sensitive.

No attempt has been made here to provide detailed technical data for the conversion processes discussed. These may be found through the *Selected Readings* and *Research Contacts* listed at the end of each chapter. Rather, the report is intended to provide sufficient information for each technique to determine whether additional investigation is warranted. Research needs and limitations are included for each area considered.

Since the panel recognizes that technical feasibility alone does not guarantee successful introduction of new technologies, the final chapter includes some of the nontechnical aspects of waste utilization.

This manuscript was edited and prepared for publication by F.R. Ruskin.

Overview

In a world of diminishing resources and increasing needs, each opportunity for the reuse of waste materials must be examined. Since most human endeavor results in some waste product, opportunities abound. This report highlights some of the effective ways to utilize organic wastes.

Although natural processes, in time, convert most organic wastes and thereby restabilize or enhance the environment, the most beneficial result does not always occur. High concentrations of wastes can overwhelm the capacity of these natural processes and cause costly pollution. A wide variety of biological, chemical, and physical processes can be substituted for simple, direct disposal, which can yield significant benefits.

Waste materials from agriculture, agroindustrial processing, animals, and humans can help fulfill the requirements for food, fuel, and fertilizer. Rising petroleum prices, foreign exchange imbalances, pollution, and soil erosion impel research in both ancient and modern methods of waste utilization.

Unproductive means of waste disposal can be replaced by methods that boost crop yields, save energy, improve the environment, and strengthen the independence and well-being of individual farmers and villages.

Caution should temper optimism, however, when initiating waste utilization projects. In each case, the alternatives must be evaluated to assess their likely impact on the environment, the economy, and society.

When selecting waste utilization projects, consideration should be given to the following factors:

- Health. When organic wastes or products derived from organic wastes are used for human or animal consumption or fertilizer, the presence of toxicants, toxins, and pathogens should be monitored and controlled to avoid hazards to man, animals, or crops. Hazardous chemicals and microorganisms are not uncommon in organic wastes.
- Quantity and quality of wastes. Both the amount of waste available at a given location and its composition help dictate or preclude various applications. Seasonal availability of a biologically fragile crop residue might warrant some form of composting, ensilage, or conversion to preservable fungal protein, for example, but not the investment required for methane generation or pyrolysis. Slaughterhouse wastes or manure, if available year-round,

could justify establishment of algal or fish culture or a productive fermentation process.

- End-use analysis. As a corollary to the concern for the character and volume of waste input, the need for the potential products must be established. A level of operation should be chosen to match the anticipated market or use.
- Technological and institutional resources. The ability of local manpower to operate and maintain the projects must be determined. Either training or continuing institutional support may be required, possibly both.
- Social change. Cultural barriers to a waste utilization process must be considered—for example, bias against food produced from wastes.

Among the chapters, discussions of certain wastes and techniques recur. Consideration of animal manures and straws as resources and cellulose degradation processes, for example, are pervasive. An index by raw material, process, and product is included.

The first chapter covers some aspects of the use of wastes in aquaculture. Although certainly aimed at food production, the use of manures and agricultural wastes in aquaculture is unique and is therefore considered separately. Food produced from wastes by other means is covered next, followed by feed production, fuel generation, land use, and integrated systems for waste cycling. The final chapter surveys the nontechnical considerations associated with waste utilization projects.

Aquaculture

Modern farming methods applied in the United States to produce channel catfish use commercial feed and incur high labor and equipment costs. Annual yields average 2,000 kg/ha. Mixed species of carp are grown in Taiwan, India, and Malaysia using animal manures and other farm wastes as feed. Annual yields range from 5,000 to 8,000 kg/ha.

The principal reasons for the productivity differences are the use of polycultures (mixed species of fish with different, noncompetitive feeding niches) and the manure-generated range of fish nutrients developed in the pond.

Excellent fish yields have also been obtained through combined duck and fish culture, through fish culture in rice fields, and through rotation systems in which vegetable gardens alternate with duck and fish ponds. Any of these practices allow one crop to make use of the nutrients in the residues of the other.

Food

Agroindustrial wastes, straws, and manures can all be converted to food by some form of bioconversion. Chemical and physical treatments of these wastes are generally not suitable for food production.

Various forms of fungal conversion are commonly used; for example, in Indonesia, peanut presscake, coconut presscake, and some soybean wastes are used to prepare palatable, nutritious foods. In addition, straw, wood waste, and animal manure have been used for mushroom production. Growing common mushrooms on composted rice straw has become a multimillion dollar business in Taiwan. Other mushroom species can be grown on sawdust, cotton waste, bagasse, shredded paper, and banana leaves. One species of mushroom can be harvested 9 days after the crop is started.

Food-grade yeasts have been grown on whey, molasses, and potato and cassava wastes.

The use of wastes for food production can expand the resource base for human nutrition. The wastes and processes used, however, must be selected and monitored to yield safe, wholesome products.

Feed

Domestic animals generally subsist on crops or crop residues inedible by man. The nutritional value of some of the residues, particularly straws, can be significantly improved through chemical, physical, or biological treatment.

Ruminants such as cattle, goats, and sheep are able to digest grasses and straws through microbial activity in their rumen (forestomach). Relatively simple treatment of straws with alkali can improve their digestibility for ruminants and require only a modest investment in time and materials. Significant live-weight gains in cattle have resulted. Crop residues can be fermented in processes that mimic rumen activity to improve digestibility for both ruminants and nonruminants.

Animal manures can also be refed as partial rations by blending and fermenting with fresh feed. Manure levels of 50 percent or more can be used with ground grains and hay.

Algae produced on wastewaters also have potential as animal feed. The combined benefit of waste treatment and feed production makes this procedure particularly attractive.

Fuels

Waste materials as energy sources resemble conventional fuels in that they vary in composition, density, heating value, and other properties. The composition of certain agricultural wastes is similar in many ways to coal, except that the wastes have a higher moisture and oxygen content and lower sulfur and ash levels. As with conventional fuels, the value of wastes as energy sources depends on cost, availability, and composition.

Gaseous, liquid, and solid fuels can all be produced from wastes. The biological production of methane (biogas) from agricultural, animal, and human wastes is perhaps best known. Recent improvements in production techniques include fixed-top, Chinese-style gas generators and bag-type generators. Both of these modifications avoid the potential mechanical and corrosion problems of the traditional floating-top gas generator.

The biological production of ethanol for fuel use is receiving much attention. Ethanol can be prepared from wastes containing sugar, starch, or cellulose. Processing is simplest, however, from starch- or sugar-based wastes. Although cellulose is the most abundant waste component, its conversion to alcohol is currently the most difficult.

Heating wastes in the absence of air (pyrolysis) can produce mixtures of solid, liquid, and gaseous fuels. For example, a ton of wheat straw heated to 500°-600°C yields about 300 kg of char, 38 liters of a tarry liquid, and 280 m^3 of gas (15,000 kj/m^3).

Heating wastes with a limited amount of air (less than needed for complete combustion) can convert substantially all the organic matter into gas of a low heat value. This gas can be used for crop or lumber drying, firing boilers, or powering diesel or spark-ignition engines. Gasification is particularly suitable for agroindustrial use where relatively dry wastes (20 percent or less moisture) are available.

Liquefaction, the process of converting solid wastes to oils through high pressure–high temperature reactions, is still in the development stage. In laboratory studies, a kg of wood can be hydrogenated to about 400 g of oil.

Land Use

Various organic wastes can be used as fertilizers and soil conditioners. Densely populated regions in Asia have used human, animal, and agricultural wastes to farm the same fields for 40 centuries.

Wastes have been used either directly on fields or after some form of treatment. In many parts of the world, treated and untreated sewage effluent is used for irrigation. Digested sewage sludge from municipal waste treatment plants is also applied to the land. Where sewage wastes are treated by pond impoundment, the bottom solids can be periodically dredged for farm use.

Composting is an effective process for conserving nutrients in wastes and converting them to a more suitable form for land application. A diversity of soil organisms act together in a compost pile to transform animal, human, and crop wastes to valuable humus.

Earthworms are also used to convert organic wastes for soil use. Earthworms consume almost any nontoxic organic waste. Their excreta (castings) have a nitrogen content equal to that of the original waste, and the physical character of the castings makes them a superior soil-conditioning material.

The water hyacinth, a prolific floating tropical plant, can be used in wastewater purification. When the water hyacinth is cultured in the effluent of sewage waste stabilization ponds, a reduction in microorganism numbers and organic contaminants results. Periodic harvest and composting of the water hyacinths return their nutrients to the land.

Integrated Systems

For optimal use of resources, essentially closed systems, in which the wastes of one process serve as the raw material for another, have been developed. Both large- and small-scale systems have been devised for use on individual farms and in agroindustrial complexes.

In these systems, animal, human, and crop wastes are all used to produce food, feed, fuel, and fertilizer. The conversion processes are combined and balanced to minimize external inputs and maximize self-sufficiency.

An experimental farm in Thailand, for example, maintains pigs and chickens, as well as a vegetable garden and fish pond. Animal wastes are used for fertilizer, fish feed, and biogas generation. Crop and human wastes are also added to the biogas unit. Liquid effluent from the biogas generator is used in the fish pond and solid residues on the garden. Periodically the locations of the garden and pond are reversed, so residues from one serve as nutrients for the other. Little is wasted in such a system.

Nontechnical Considerations

The feasibility of waste utilization projects depends not only on factors such as physical resources and needs but also on public health and institutional, economic, and cultural considerations.

The successful implementation of a new technology requires prior examination of the environment surrounding those it is intended to benefit, and the technology must be adjusted to this environment. Care should be taken with any new technology utilizing human and animal wastes because of the potential to endanger public health.

The choice of technology may also affect employment by selection of a labor-intensive technique rather than a capital-intensive one.

Consideration must also be given to long-range economic consequences; a given technology may widen rather than narrow income inequalities.

Finally, institutional support is often required not only for training but for maintenance and monitoring. Therefore, coordination among disparate groups and agencies may be needed to provide such support.

In any project that requires the removal of the bulk of crop residues from the field, consideration must be given to the potential for erosion or other kinds of soil degradation.

Thus, although technical feasibility is essential for the success of a project, it is no detraction from the project's potential to emphasize that more than technical feasibility is required for implementation.

1 Aquaculture

The use of organic wastes in fish culture probably predates written history. Silkworm wastes were used in pond-fish culture in China more than 4,000 years ago. The earliest published work on the use of wastes in fish culture was by Fan Lai in China around 460 B.C. Fish culture in India and other parts of Asia may be equally ancient. Early Roman writers, including Pliny, gave directions for the use of stable sweepings and other organic wastes in fish ponds.

To a large extent the nutrients that support fish growth in waste-fed ponds are incorporated in the natural foods that develop in the pond. This food consists of small plants and animals—phytoplankton and zooplankton. Owing to the minute size of these organisms, harvest by man is both time consuming and energy consuming, and conversion to a food acceptable by man is difficult. Fish, however, if stocked at the right density and species combination, can convert plankton quite efficiently to a more palatable form of protein. Moreover, it is more productive to grow fish that feed on plankton, such as carp or tilapia, than to culture a predator, such as bass, which feeds primarily on other fish. From the farmer's viewpoint the carp can be a producer of food from inedible sources, whereas the bass is a net consumer of edible food.

Suitable ponds can often be constructed on marginal land, dunes, or swampy land unsuitable for agriculture. They can be utilized as storage facilities for irrigation water, and occasionally dredged for fertilizer. Aquaculture, therefore, can complement agriculture in increasing food production. Fish production can also be linked to existing waste treatment facilities to provide additional biological treatment.

Direct and Indirect Feeding

A wide variety of organic wastes can be used successfully in aquaculture. Some wastes serve as direct feed for fish—agricultural and kitchen residues; trash fish; and agroindustrial by-products such as rice bran, oilseed cakes, and distillery, slaughterhouse, and fishery industry residues.

Indirect use can be made of the wide variety of agricultural fibrous wastes. The principal wastes used in aquaculture are animal manures, a major component of which is crude fiber. The fiber and mineral components of manure serve as indirect feed by enhancing natural productivity in the pond. Decomposition of these wastes increases the production of bacteria and fungi, which serve as food for a multitude of organisms in the pond such as protozoa and zooplankton. When the wastes are mineralized to their inorganic components, they enhance the growth of phytoplankton, a basic part of the food web.

Through this microbial activity, in which low-nutritional-value wastes reenter the food web and are upgraded in protein content, the pond performs an external function for fish similar to the internal function of the rumen in cattle or sheep.

The characteristics of wastes required for direct or indirect feeding are different. Wastes that serve as direct feed must be large enough to be taken up by the fish. Wastes that are used indirectly should be finely divided so that they remain suspended in the water and spread through the pond. The relatively larger surface area of smaller particles also provides more sites for bacterial attack.

Any animal manure that is easily divided into fine particles is suitable for use in ponds. Fresh manures are more easily dispersed through the water column and are more rapidly assimilated into the food web than dry manures.

The rate and volume of organic waste addition to fish ponds are of great importance. Sporadic applications of large amounts of organic matter are of little benefit to fish production and can cause oxygen deficiency and con-

FIGURE 1.1 Pigpens on the edge of fish ponds facilitate manure addition. (D. H. Buck)

sequent fish kill. Following such applications, bacterial production increases to a high level, and the respiration associated with this microbial growth consumes most, if not all, of the available oxygen in the water. On the other hand, frequent applications of smaller amounts of organic material allow development of protozoa and zooplankton that consume the bacteria and prevent their overpopulation.

The amounts of waste can then be gradually increased to higher levels without creating hazards. Daily applications of fresh manure are beneficial to the productivity of the pond and safer than less frequent applications. Both these conditions, the use of fresh manure and frequent application, can be met by confining animals so that their manure drops or flows directly into the pond (Figure 1.1).

Since the organisms that develop in the pond through indirect feeding are rich in protein (50–60 percent dry weight), simple, carbohydrate-rich crop wastes can be used as direct feed for fish. Thus the natural protein-rich organisms developed in indirect feeding can be supplemented with nutritionally poor wastes such as rice bran to increase fish production in the pond. The combination of direct and indirect feeding allows utilization of both animal manures and some agricultural residues to give high yields of fish.

Fibrous residues such as rice straw can also serve as a base for the production of the bacteria-protozoa complex in the pond. The straw must, however, be supplemented with nitrogen and phosphorus fertilizers to provide the carbon:nitrogen:phosphorus ratios essential for the growth of bacterial cells–about 100:5:1.

Polyculture

Each species of fish feeds on a more or less defined array of organisms. With indirect feeding the production of a multiplicity of organisms in the food web, such as algae, protozoa, and zooplankton, is enhanced. Since one fish species alone (monoculture) cannot utilize all of this natural food, an imbalance of organisms can develop. Unchecked proliferation of the organisms in one stratum of the food web can drive down the oxygen level in the pond to a hazardous level. Moreover, part of the nutritional value of the wastes is diverted to nonproductive use. These limitations may be alleviated by stocking several fish species with feeding habits that match the organisms produced. This multiple stocking, particularly advantageous in waste-fed ponds, is termed polyculture (Figure 1.2).

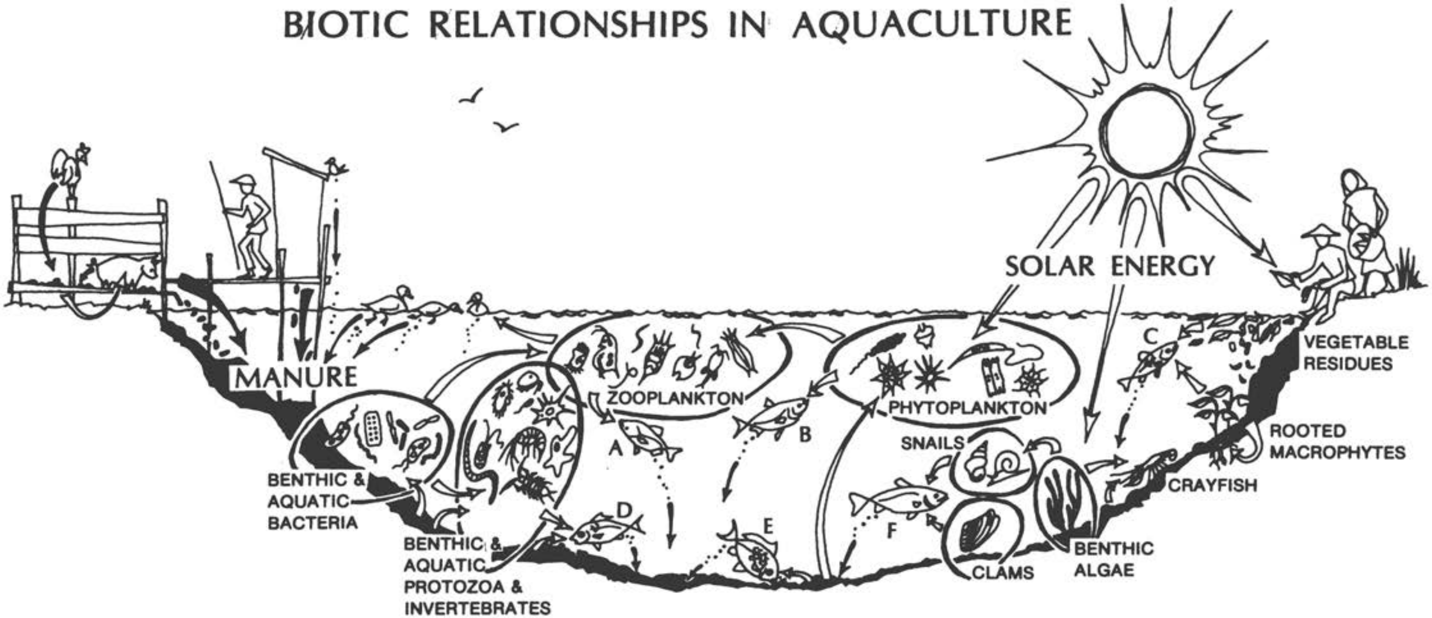
In addition, when only one species of fish is grown, metabolic waste products can build to levels that foul the water and inhibit growth. Costly flushing or recycling systems can be used to prevent this pollution, but the use of a carefully chosen polyculture is a better solution.

FIGURE 1.2 Harvesting from a fish polyculture in a waste-fed pond near Barrackpore, India. (D. H. Buck)

Polyculture systems are commonly integrated with livestock production. Ponds are frequently located so that wastes from pigs or chickens drop directly into the pond. For cattle, sheep, or goats it may be more practical to transport the manure to the pond. Another common practice is to use fish ponds as production units for ducks or geese so that the manure is deposited directly into the pond.

Polyculture can involve a wide variety of combinations, including multiple fish species; fish and invertebrates (such as clams, prawns, and crayfish); or fish, shrimp, and algae. In Taiwan clams and milkfish are cultivated in ponds constructed from mangrove swamps. The most widely used combinations are those involving Chinese carp. A typical pond might include silver, grass, black, bighead, and common carp.

Grass and silver carp are herbivorous. Grass carp consume aquatic vegetation and will also feed on terrestrial plant residues such as vegetable tops and grass clippings. Silver carp, by means of their special filtering apparatus, consume large quantities of phytoplankton. Bighead carp feed primarily on zooplankton, and black carp consume snails and other benthos. Common carp feed on benthic animals and detritus. In scavenging pond bottoms, common carp stir up sediments which create turbidity and help prevent excessive growth of undesirable aquatic vegetation. Perhaps more important, organic particles are suspended that are enriched through colonization by bacteria and filtered from the water column by fish such as the silver carp. These biotic relationships are shown in Figure 1.3.



LEGEND

- ⇦ FLOW OF ENERGY AND/OR NUTRIENTS
- ◀ INPUT OF MANURE

FISH SPECIES

A BIGHEAD CARP *(Aristichthys nobilis)*
B SILVER CARP *(Hypophthalmichthys molitrix)*
C GRASS CARP *(Ctenopharyngodon idellus)*
D MUD CARP *(Cirrhinus molitorella)*
E COMMON CARP *(Cyprinus carpio)*
F BLACK CARP *(Mylopharyngodon piceus)*

FIGURE 1.3 Biotic relationships in aquaculture. (D. Dindal)

The herbivorous fishes perform a special function. The Chinese say, "if you feed one grass carp well, you feed three other fishes." Both grass and silver carp have long, simple guts and relatively inefficient digestive systems. They must consume massive quantities of vegetation to support their rapid rates of growth (commonly 3-4 kg/year). For example, a grass or silver carp may consume its own weight in aquatic vegetation each day. Since only a small portion is completely digested, both the grass and the silver carp excrete large quantities of partially digested materials, which not only provide a direct food to the bottom-feeding fishes, such as the common carp, but also stimulate production in other parts of the food web.

An outstanding example of the benefits of polyculture on fish yields is found in Israel. Over the past 40 years average fish yields have risen from about 1,500 kg/ha to almost 4,000 kg/ha, primarily through the effective use of polyculture. In Illinois, where the growing season for warmwater fish can be as short as 170 days, the advantages of polyculture have also been demonstrated by Buck et al. For channel catfish fed commercial high-protein pellets, the maximum production was about 1,500 kg/ha. When the same ponds were manured and stocked with a polyculture of Chinese carp, the net gain was increased to 4,585 kg/ha. This threefold increase in production was accomplished using only swine manure and sunshine.

Production in a polyculture varies widely and is dependent upon such factors as climate and quality of manure or other organic enrichment; species, numbers, and sizes of fish stocked; depth and natural fertility of the pond; and individual management practices. A recent Food and Agriculture Organization (FAO) mission to China reported a range of from 1,500 kg/ha/year in an area north of the Great Wall to 3,750 kg/ha/year south of the Yangtze River. Similar fish production is achieved in Hong Kong, Singapore, and Malaysia. An intensively manured pond in Taiwan, stocked with Chinese carp, mullet, and sea perch, has produced up to 7,700 kg/ha/year, and the Israelis have achieved similar rates of production utilizing combinations of carp, mullet, and tilapia. The Indians utilize a combination of their own major carp species (rohu, mrigal, and catla) and Chinese carp to achieve yields in the range of 7,000-8,000 kg/ha/year.

The Hungarians are recognized experts in the combined production of ducks and fish. In ponds stocked with a polyculture of Chinese carp and hybrid ducks that can mature in 46 days, they can produce 2,500 kg of ducks (three crops) and 2,500 kg of fish in the April-September fish-growing period (Figure 1.4). Duck and fish polyculture is also practiced in India (Figure 1.5), Hong Kong, and Taiwan.

As has been demonstrated in both Israel and China, it is possible to utilize aeration, supplementary feeding, multiple stocking and cropping, and other intensive methods to achieve experimental production rates as high as 18,000 kg/ha/year, but average rates of sustained production throughout most of the world are probably in the range of 300-500 kg/ha.

FIGURE 1.4 Duck and fish polyculture in Fonyód, Hungary. (D. H. Buck)

FIGURE 1.5 Duck and fish polyculture in West Bengal, India. (A. Ghosh)

Use of Animal Manures

Amounts of animal manures must be carefully controlled. In Israel it is considered safe to use 75-100 kg/ha/day (dry organic matter) of manure. In Hungary 500-600 ducks per hectare are raised on a pond containing a carp polyculture. In Taiwan the dried manure from as many as 100 fattening pigs may be utilized per hectare of pond area. Also, the combined wastes of 1,500 ducks, a small flock of chickens, and 30 pigs have been used in Taiwan in a 1.5-ha pond. In Illinois the fresh manure from as many as 85 fattening pigs per hectare has been used in a Chinese carp polyculture. In China as few as 30–45 pigs are believed to supply sufficient manure for 1 ha of fish pond.

In Alabama, Nerrie and Smitherman used pelleted chicken manure to feed tilapia stocked at approximately 10,000/ha. Up to 120 kg/ha/day of pelleted chicken manure was considered safe. Average fish production of 14 kg/ha/day resulted from using chicken manure. The pelleted manure supplemented with soybean and corn meals increased fish production to 22 kg/ha/day.

In Israel, Schroeder has developed semiquantitative guidelines for the use of various manures. The rates are based on the dry organic matter (DOM) content of the manure—that is, the dry weight minus the ash content—and are related to the total fish biomass in the pond.

For example, cow manure (measured as DOM content) should be added daily at a rate of 3-4 percent of the fish biomass of that day. On the same basis, pig manure should be added at 3-4 percent, chicken manure at 2.5 percent, and duck manure at 2 percent. From daily rates of manure production, animal stocking rates can be calculated to provide (but not exceed) 75-100 kg DOM/ha/day.

Using these amounts, Schroeder suggests fish-stocking densities of 8,000-20,000/ha. For larger fish at harvest, 8,000-10,000 fish/ha should be stocked; for smaller fish, 15,000-20,000/ha. The successful control of water quality and fish survival depends on the proper number and distribution of consumers for the organic materials deposited or developed in the pond. In manure-fed ponds, 10-15 percent of the fish should be common carp or similar bottom-digging fish. With 10-15 percent filter feeders, such as silver carp, and the remainder *Tilapia (Sarotheradon) aurea* or *T. nilotica*, a well-balanced, productive pond can be established.

Use of Domestic Wastes

The use of fish ponds for domestic wastewater treatment has been neglected in most parts of the world. Food-producing systems for sewage treatment, however, are of growing interest. In areas of limited capital resources, inexpensive land, and limited supplies of water, fish pond systems for wastewater treatment can have great value. In some areas, latrines are erected at the edge of fish ponds to allow direct addition of human wastes (Figure 1.6).

In Munich, Germany, treated sewage effluent is used as a source of nutrients for carp farms. Yearly production ranges from 400 to 800 kg/ha.

In the United States polyculture has been used to upgrade sewage effluent. Using a combination of *T. nilotica*, fathead minnows, golden shiners, and channel catfish in the final treatment lagoons, effluent water quality was improved. No pathogens were detected in the lagoons containing fish, nor were any found in the fish sampled.

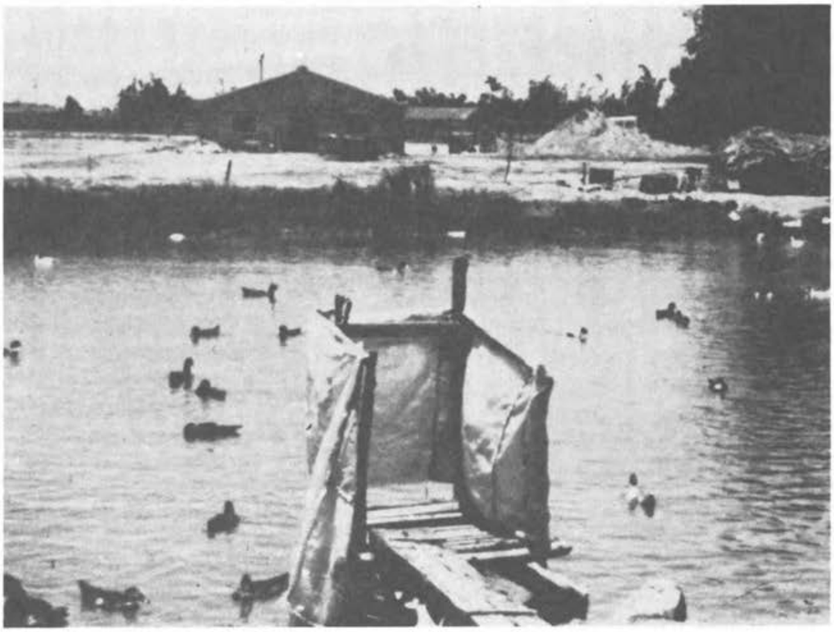


FIGURE 1.6 A simple latrine permits direct addition of human wastes to a duck and fish pond in Taiwan. (D. H. Buck)

Another U.S. study combined treated sewage effluent with seawater in a system designed to recycle nutrients into commercially valuable marine organisms. Seawater and sewage effluent were used to grow marine algae. In a continuous flow system, algae were fed to bivalve molluscs maintained in trays. The algae removed nutrients from the wastewater, and molluscs fed on the suspended algae. Other animals, including lobsters and flatfish, consumed wastes produced by the molluscs and invertebrates that fed on the wastes. In a final step, the effluent was passed through a bed of seaweed to further reduce the residual nutrients.

Penaeid shrimps have been grown in the United States in brackish ponds receiving treated domestic sewage effluent. Without supplemental feeding, a tenfold increase in weight over a 10-week period was reported.

In India a combination of tilapia, three Indian major carps (catla, rohu, and mrigal), and common carp were grown in a 25-ha pond fertilized with Calcutta sewage (Figure 1.7). Carp fingerlings were stocked at 8,850/ha. The distribution was 35 percent mrigal, 30 percent common carp, 20 percent catla, and 15 percent rohu. *T. mossambica* were stocked at 150–200 kg/ha. Carp and tilapia were harvested periodically by operating a dragnet. Generally, individual tilapia weighing more than 40 g and carp weighing around 500 g were harvested 3 months after stocking. In 1 year 8,500 kg/ha of tilapia and 3,315 kg/ha of carp were harvested.

FIGURE 1.7 In Calcutta, India, a large impoundment for municipal sewage is used for fish polyculture. (A. Ghosh)

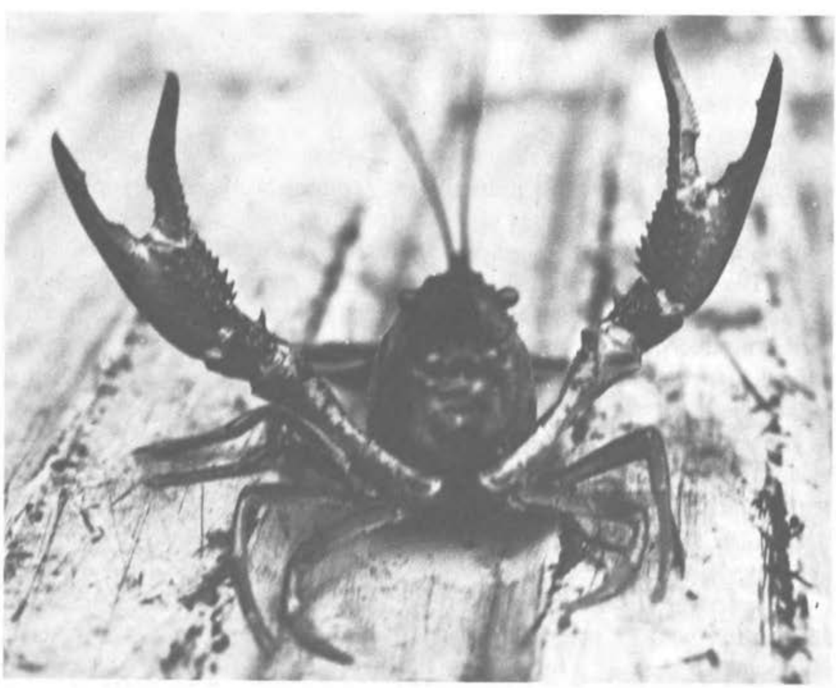


FIGURE 1.8 A red swamp crayfish (*Procambarus clarkii*) suitable for culture in rice fields. (J. Avault)

A continuing Arkansas study is evaluating the contribution of silver and bighead carp to domestic sewage treatment. A volume of sewage equivalent to that produced by a community of 2,000 flows through a series of six 1.6-ha oxidation lagoons. The carp are stocked in the last four ponds in the series and consume algae and other organic material. The consequent reduction in biochemical oxygen demand, suspended solids, and fecal coliforms provides a final effluent that is well within local and federal environmental protection standards. With further study and development, systems of this type may eliminate the need for small communities to construct more expensive mechanical treatment plants. Moreover, such systems can also produce large quantities of usable protein.

Scientists at Gloucester Point, Virginia, report that the American oyster grown in polluted waters can be purified by holding it in clean seawater for 2 to 4 days. The oyster makes efficient use of fine suspended particles and hence is a good organism for water treatment. Postgrowth purification in clean water may then permit the oyster to be used for human consumption.

Agricultural Wastes

Agricultural wastes can be used directly in the field by alternating or combining terrestrial and aquatic crops. One example is the combined production of rice and crayfish as practiced in Louisiana (Figure 1.8). Rice is planted in March or early April. Brood crayfish are seeded into the fields in June or July. They burrow underground where they remain during the rice-growing season. In August water is removed from the field to facilitate rice harvest. The fields are reflooded in mid-September, at which time the crayfish are flushed from their underground burrows. Young are released and feed on decaying rice stubble and microorganisms associated with rice straw decomposition. The crayfish harvest may begin in late November and extend into April or May. Farmers harvest up to 1,000 kg of crayfish per hectare. The gross return for crayfish may exceed that from rice (see Table 1.1 for comparisons).

TABLE 1.1 Comparison of Rice, Soybeans, and Crayfish Returns in Louisiana

Crop	Average Production per Hectare	Price per Bushel or Kilogram ($)	Gross Revenue per Hectare ($)
Rice	250 bushels	3.50	875.00
Soybeans	90 bushels	7.00	630.00
Crayfish	1,000 kg	1.15	1,150.00

There are a number of advantages to the rice-crayfish system. First, crop residues are turned into protein. In addition, the crops grown in sequence benefit each other. Crayfish till the soil by their feeding activity, add nutrients to the field from their wastes, and consume aquatic weeds as well as rice residues. When rice is replanted following crayfish harvest, the soil need not be tilled. Instead, presprouted rice can be broadcast directly on the mucky soil bottom, or seed rice can be planted without tilling, thereby saving time and energy.

Tilapia can also be cultured in rice fields during the growing season to convert insects and other aquatic organisms to edible protein (Figure 1.9). *T. aurea* and *T. nilotica* appear to be desirable species. Monosex culture of *T. mossambica* is also suitable. In the Philippines, de la Cruz has obtained 200 kg/ha of *T. nilotica* from stocking 5,000 fingerlings per hectare. When *T. nilotica* and common carp fingerlings were stocked at 4,000 and 2,000/ha, respectively, total yields of 290 kg/ha were obtained.

In West Java several types of combined vegetable-fish culture are practiced. In rice paddies, common carp have been grown (1) between rice harvest and replanting, (2) during part of the rice-growing season, and (3) in fields left fallow for a season.

In the month between harvest and planting, common carp seeded at 40 kg/ha yielded 60 kg/ha. During 2.5 months of the growing season, common

FIGURE 1.9 Rice and fish culture in West Bengal, India. (A. Ghosh)

carp stocked at 50 kg/ha yielded 150 kg/ha. Common carp stocked at 50 kg/ha in a fallow rice field yielded 600 kg/ha in 4 months.

In addition, both kangkung (*Ipomoea reptans*) and genjer *(Limnocharis flava)*, popular shallow water vegetables, have been grown with common carp. Fingerling carp stocked at 100 kg/ha after kangkung seedlings were established yielded 150 kg/ha in 1 month. From about 60 kg/ha of common carp stocked in a genjer pond, about 240 kg/ha were obtained in 3 months.

Mendong (*Fimbris globusa*), a fibrous aquatic plant used for weaving hats, bags, and mats, is grown for home industry in West Java. Tilapia (30 kg/ha) and common carp (90 kg/ha) grown in the mendong ponds yielded 90 kg/ha and 180/ha respectively after 3 months.

Industrial Wastes

Industrial wastes have also been used in fish culture. In Puerto Rico, rum distillation wastes and pharmaceutical wastes have been evaluated for the culture of tilapia. Fish reared on the by-products of antibiotic production achieved a growth comparable to that of the commercially fed control. Production from the fish fed on distillery wastes was lower than that of the commercially fed fish, but 2 to 3 times higher than the unmanaged group.

The rubber processing wastes in Malaysia have particular potential for fish culture. Ammonia, used to prevent premature coagulation of latex, is lost with other processing effluents and could be used in algal-fish production.

Diluted sugar-beet-processing wastewaters have been used for fish culture in Poland. The wastes are impounded without fish over the winter to allow for some anaerobic self-purification. In spring, the wastes are further diluted and oxygenated and fish are introduced. When the wastewaters are emptied in the fall they have been purified to the extent that they cause no pollution in the receiving waters.

In Peru a combination of slaughterhouse wastes and fish meal is used as feed in trout farming.

In the United States a waste treatment system using brine shrimp (*Artemia salina*) upgrades part of the effluent from a petrochemical complex. These waste streams contain small amounts of organic matter and large amounts of salt. Bacteria remove the organic material, and algae are grown on this effluent. In a final pond, brine shrimp consume the algae, the result being a clear effluent.

Although fish culture on industrial wastes avoids the possibility of disease transmission by animal wastes, it does not preclude contamination from industrially generated toxicants.

Limitations

Health Problems

Fish may carry human pathogens in or on their bodies, and these pathogens may subsequently infect those who handle, prepare, or eat the fish. There is little risk to those who eat the fish except when fish are eaten raw or only partially cooked, since thorough cooking will destroy the pathogens. Those who handle or prepare the fish, however, would be subject to infection, and the preparation area may become contaminated.

Although most studies on human pathogens in fish are related to sewage-polluted natural waters, the observations apply to fish farming as well. There is extensive evidence that the intestinal flora of humans are not the normal resident flora of fish. Fish raised in contact with these bacteria, however, may acquire substantial numbers on their bodies and in their intestines. Fecal coliforms, fecal streptococci, and salmonellae are easily isolated from fish grown in polluted waters. The survival of enteric bacteria in fish intestines or on fish transferred to clean water is generally reported as being less than a week, with some reports of up to several weeks.

Another health hazard associated with fish farming is the transmission of parasitic worms to man through an intermediate fish host. *Clonorchis sinensis, Opisthorchis viverrini*, and *O. felineus* are parasitic flatworms that cause liver infections in man. All are associated with excreta-fed fish ponds and are transmitted when fish are eaten raw or partially cooked. In some areas of the Far East the prevalence of infection can reach 60 percent. Transmission of these flukes is associated with the direct enrichment of ponds with nightsoil or raw sewage. Since the parasites' eggs will settle readily, sewage that has been pretreated or settled prior to pond introduction can control their transmission. A week's storage in nightsoil or digestion in a biogas generator will usually result in the death of the eggs.

Transmission of schistosomiasis to fishermen can also occur in ponds and can be prevented by using sewage treated in stabilization ponds or stored nightsoil.

Crayfish should not be introduced into regions where onchocerciasis, the river blindness disease, is prevalent. The *Simulium* fly that transmits this disease sometimes attaches its larvae to the backs of river crabs; it is possible that crayfish would be similarly used.

Training

Fish culture in ponds is not as simple as raising cattle in pastures. A pond operator needs experience and knowledge in the manipulation of fish environments, or productivity will be greatly impaired. Technical service to the pond operator by extension specialists is usually needed.

Capital

Start-up costs for pond construction and stocking may require a capital investment beyond the means of many potential users; therefore, mechanisms for providing subsidies or loans may be required.

Labor

Intensive care and management are often required. Reports from India, Indonesia, Thailand, and the Philippines indicate, however, that even with low-level management practices, good yields are obtained.

Social and Cultural Problems

Fish grown in ponds that utilize wastewater may not be accepted as human food; however, "clean" wastes such as straws do not present this problem and could be used instead.

There are also strong, traditional cultural deterrents to eating fish in parts of Africa and Asia, often related to religious belief or concern with social status. The Beja, pastoralists of the Red Sea borderlands of Egypt, Sudan, and Ethiopia, are reported to reject fish even when in extreme need. Similar attitudes, that fish are unclean food and that social status is enhanced by refraining from fishing and eating fish, are also found among the Nilotes and Bantu in East and South Africa. In India it has been estimated that nearly a third of the population do not eat fish. Most of their avoidance stems from religious conviction, especially athisma (nonviolence to living creatures), central to Jain and Hindu philosophy. Brahmins and members of other high castes refuse fish because fishermen are untouchable; as upper caste members, Brahmins would become ritually defiled by eating fish. Where traditional rather than religious factors cause avoidance of fish, it may be possible to process the fish in a way that will prove more acceptable.

Toxicants

Another constraint on the use of wastes and wastewater is the presence of toxicants. In agricultural wastes these may be residues of insecticides and herbicides used on the farm and discarded in the wastes. Some of these insecticides are extremely poisonous to fish. The application of 6–10 g/ha of Endrin (a chlorinated hydrocarbon insecticide) may cause total fish kill.

In municipal wastewater residual detergents cause problems. A concentration of about 10 ppm of some detergents can be lethal to fish, and sublethal concentrations can hamper fish growth. Some municipal wastewater may contain up to 20 ppm of detergents. The effect of the detergents can be offset either by pretreating the wastewater in a sewage treatment plant (which will also reduce the organic nutrient content) or by diluting with fresh water to a concentration that will not affect the fish.

Industrial wastes, when used directly in ponds or when mixed in municipal wastewater, may contain toxicants. These may kill the fish or, as in the case of phenols, impart an off-flavor.

The presence of toxicants of any sort must be avoided or reduced to a nonhazardous concentration. Public health programs should provide the necessary protective measures that monitor and control residue accumulation.

Research Needs

It is clear that there is a strong interaction between the fish population and the kind and amount of waste applied to the pond. With an increase in the organic load, more natural food is produced.

To utilize this food most effectively, greater numbers of fish are required. Moreover, since each species in a polyculture feeds from a different level of the food web, which varies with a change in the kind or amount of waste, the stocking density of each of the species in the polyculture must be modified. That is, the numerical ratio of the species must be adjusted to match the kind and amount of wastes used. Not enough is known about these relationships. In addition, more information is needed on the relationships of direct and indirect feeding.

The integration of aquaculture with other forms of agriculture requires study. Research is needed on combining beef, swine, or poultry production and various waste utilization systems (such as methane generation) with aquaculture. This integration requires careful balancing of each component; the combination must be studied as one unit.

The method of application and the distribution of waste over the pond area is an important factor, especially in a large pond. Consideration should also be given to treating the waste outside the pond before application—through composting, for example, or use in biogas generation.

There is a special need in rice-fish culture to produce disease-resistant rice varieties and to develop techniques that can eliminate the need for pesticides that are harmful to fish and crayfish.

The large amount of crude fiber (for example, straw) available in many parts of the world can be used more effectively in fish ponds if it is pretreated. Accordingly, pretreatment by alkaline hydrolysis should be evaluated. Such pretreatment can greatly increase the availability of the cellulose to bacterial action and increase the bacterial yield. Pretreatment through aerobic decay (composting) can produce an amount of bacterial cells up to three times greater than can anaerobic decay of the same amount of substrate.

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2 Food from Wastes

The dramatic increase in agricultural production over the past several decades has been largely based on increased energy inputs in the form of fertilizers, herbicides, pesticides, and mechanization. Reduced use of energy in agriculture, because of rising costs or diminishing availability, will have a profound effect on crop yields and will require more efficient use of the crops grown.

Part of the need for increased world food supplies can be met through the conversion of crop wastes to food. (However, the effect of this removal on soil fertility must be carefully considered.) The production of food from wastes is not restricted to use of food crop residues, however. Wastes from cotton and paper mills and even animal manures can represent potential substrates for conversion to food. Although the need for protein in the human diet is inescapable, it need not be derived from meat, fish, or vegetables.

This section will deal with the conversion of agricultural residues and wastes to fungi, yeasts, and bacteria for use as food.

Fungal Protein

Fermentation

In Indonesia several agricultural residues are converted to food through traditional fermentation processes. The raw materials used are peanut presscake, coconut presscake, soybean hypocotyledons, and the residue from preparing soybean curd (tofu).

Oncom (ontjom) is prepared by soaking peanut presscake in water and then steaming. By allowing mold to grow on the peanut presscake for about 40 hours, a food is produced that is used in the daily diet of some 25 million people in Indonesia.

The microorganisms used are *Rhizopus oligosporus*, which produces oncom with a black color, and *Neurospora sitophila*, which produces red or orange oncom. Enzymes produced by the mold penetrate the substrate and make the mass both more digestible and more flavorful. Oncom processing also produces beneficial amounts of vitamin B-12.

Tempeh bongkrek is prepared from shredded coconut presscake, with *Rhizopus oligosporus* as the inoculum. A well-made product is a compact cake that is completely covered and penetrated by the white mold mycelium. Occasionally, however, the mold mycelium does not develop, and a toxin-producing bacteria, *Pseudomonas cocovenenans*, overgrows the mold. The mass then remains granular and loose, becomes slimy, develops a putrid odor, and becomes yellow. Such poorly fermented products are poisonous. Bongkrek toxin consist of two substances, toxoflavin and bongkrek acid, which have been responsible for many deaths in Indonesia. In his paper on Indonesian fermented foods, Winarno cites two approaches to reduce the possibility of bongkrek poisoning. One involves adding dried leaves from calingcing (*Oxalis sepuin*), which probably controls the growth of *P. cocovenenans* by reducing the pH. The addition of 1.5-2.0 percent of NaCl to the presscake also appears to suppress the formation of bongkrek acid.

Tempeh gembos and oncom tofu are prepared from the residue obtained in making soybean curd. Inoculating this residue with *Neurospora sitophila* results in an orange-red product like the oncom from peanut presscake. This foodstuff is known as oncom tahu. When *R. oligosporus* is used as inoculum, a grayish product, tempeh gembos, is obtained.

Tempeh mata kedele, as reported by Gandjar, is prepared from soybean hypocotyledons. During traditional tempeh processing, when the soaked soybeans are being dehulled, the hypocotyledons float to the surface. They are collected, boiled, separated, cooled, and inoculated with *R. oligosporus.* After fermentation for 2 days, the product tempeh mata kedele is obtained.

Mushrooms

Higher fungi—mushrooms—have been used as human food for centuries. Of more than 45,000 species of fungi technically described, about 2,000 species are known to be edible. Of these, fewer than 25 species are widely accepted as food, and only about 10 have become commercial items.

Despite this lack of exploitation, mushrooms are potential contributors to the world's food supply since they have the ability to transform nutritionally valueless wastes into highly acceptable, nutritious foods. Special considerations in mushroom culture include labor, land, and environmental conditions.

Mushroom culture is labor intensive. In the past decade, Taiwan has become the world's second largest producer of the common mushroom, using predominantly hand labor. Availability of labor may not be a problem in many areas.

While land availability is a limiting factor in most types of food production, mushroom culture requires little space. With current technology, high yields can be obtained with intensive, stacked-tray culture.

Depending on the mushroom species, substrate preparation and control of temperature, humidity, light, and competing organisms are more or less stringent. On the basis of diverse cultivation practices reported, it may be possible to select a species to suit the circumstances of a given locale in terms of environmental conditions and available wastes.

Table 2.1 indicates some of the wastes and temperature ranges used in mushroom cultivation. The two temperature ranges shown for each species are for the periods of inoculation through subsurface growth (spawn running) and surface appearance through harvest (fruiting). The approximate degree of environmental control required for the various species is also indicated.

TABLE 2.1 Mushroom Cultivation Conditions

Species	Temperature, °C Spawn Running	Temperature, °C Fruiting	Level of Environmental Control Required[a]	Waste Substrate
Agaricus bisporus (common mushroom)	20–27	10–20	++++	composted horse manure or rice straw
Agaricus bitorquis	25–30	20–25	++++	composted horse manure or rice straw
Auricularia spp. (ear mushrooms)	20–35	20–30	+++	sawdust–rice bran
Coprinus fimetarius	20–40	20–40	+	straw
Flammulina velutipes (winter mushroom)	18–25	3–8	+++	sawdust–rice bran
Lentinus edodes (shiitake mushroom)	20–30	12–20	++	logs or sawdust–rice bran
Pholiota nameko (nameko mushroom)	24–26	5–15	+++	logs or sawdust–rice bran
Pleurotus ostreatus (oyster mushroom)	20–27	10–20	+	straw, paper, sawdust-straw
Stropharia rugoso-annulata	25–28	10–20	++	straw, paper, sawdust-straw
Tremella fuciformis (white jelly mushroom)	20–25	20–27	+++	logs or sawdust–rice bran
Volvariella volvacea (straw mushroom)	35–40	30–35	+	straw, cotton wastes

Source: Kurtzman, 1979.

[a] ++++, greatest; +, least.

The most widely cultivated species are the common, shiitake, straw, and oyster mushrooms. Grown on a more limited scale are the winter, ear, white jelly, and nameko mushrooms. The *Stropharia* and *Coprinus* species are not widely grown but are included here for their potential value in waste conversion.

Common Mushroom In the commercial culture of the common mushroom *Agaricus bisporus* (Figure 2.1) in Taiwan, rice straw serves a dual purpose. On the basis of studies that began in 1953, a rice straw compost was developed as a substitute for horse manure compost ordinarily used for these mushrooms. The use of rice straw for compost by the mushroom growers (Figure 2.2) has provided income for local farmers from an agricultural residue often discarded. After use for mushroom growing, the compost can be returned to the field as fertilizer.

In addition, rice straw is used to cover bamboo frames in the construction of mushroom-growing shelters (Figure 2.3). Lined with plastic sheeting to help control humidity and improve pest control, these shelters have proved to be productive units, yielding up to 120 kg/m^2 each season.

In countries with tropical or subtropical climates, a newly marketed species, *Agaricus bitorquis*, offers an interesting alternative to *A. bisporus*. One of the chief characteristics of *A. bitorquis* is that it fruits at higher temperatures (25°C) than *A. bisporus* (10–20°C). *A. bitorquis* is also resistant to the persistent virus that causes dieback disease in the common mushroom. It has also been observed that *A. bitorquis*, when properly harvested, can be kept a few days longer than the common mushroom and is more resistant to pressure and bruising. A disadvantage of *A. bitorquis* is that since it has been grown commercially for only a few years, production experience is limited. Moreover, all of the extensive preparation and protective measures required by *A. bisporus* are also needed for *A. bitorquis*.

FIGURE 2.1 A cluster of *Agaricus bisporus* (*Asian Business*)

FIGURE 2.2 While mushroom-growing houses are being erected, rice straw compost is prepared for use. (J. C. Lee)

FIGURE 2.3 Completed mushroom houses covered with rice straw. (*Asian Business*)

Shiitake Mushrooms Primitive culture of the shiitake mushroom began in China nearly 800 years ago. Although shiitake is usually grown on oak and chestnut logs, it gained its name from its occurrence on the shii tree (*Castanopsis cuspidata*). Scrub oak (*Quercus gambelii*), a weed tree not suited for paper or lumber, has also been used.

Outdoor cultivation on logs requires up to 2 years for the first harvest. The procedure involves drilling small holes in stacked logs and inoculating with wood chips containing shiitake mycelium. About 50 kg of mushrooms can be obtained from a cord of wood in the first crop. Yearly crops of 40-50 kg continue for another 4 years before the logs deteriorate.

More interesting from the standpoint of waste utilization is the indoor cultivation of shiitake on farm and forest cellulose waste materials. At the University of Wisconsin (USA), through continued strain selection, Wu obtained an isolate that produced small fruit bodies on this medium. Fruits were obtained after only 2 months and fruiting continued for another 2-4 months. An average of about 260 g of fresh mushrooms per kg of dry waste was obtained. Wu also demonstrated that the feed quality of composted farm and forest wastes was raised to the level of alfalfa through culture of shiitake.

Straw Mushroom The straw mushroom (*Volvariella volvacea*) is most commonly grown on rice straw. Other substrates have also been used, including sorghum and wheat straw, maize residues, bagasse, banana leaves, tobacco stems, water hyacinth, sawdust, and cotton wastes.

Culture on rice straw is reasonably straightforward. A bed is prepared by using clean, fresh rice straw that has been soaked in water for a day and drained. Typically, multiple layers of straw, bundled or loose, are placed on a raised bed. The bed is inoculated with spawn, and with daily watering to keep the bed moist, mushrooms begin to emerge in about a week.

Yields of straw mushrooms are strongly dependent on the substrates and culture methods used. Yields in indoor production are much higher than in open-field growth. In Hong Kong, for example, outdoor yields averaged about 7 kg of fresh mushrooms per 100 kg of dry straw; the average yields in indoor experiments were about 28 kg of fresh mushrooms per 100 kg of dry straw. Substituting composted cotton waste for straw has given yields as high as 45 kg of fresh mushrooms per 100 kg of dry substrate. Figure 2.4 shows straw mushrooms growing on a straw-cotton substrate.

Oyster Mushroom In nature, the oyster mushroom (*Pleurotus* species) grows on dead trees, which are generally poor in nutrients. Substrates such as corncobs, straws (Figure 2.5), woodshavings, sawdust, nutshells, and vegetable wastes are all suitable for *Pleurotus* production.

Pleurotus has also been grown successfully on shredded paper. A sterilized

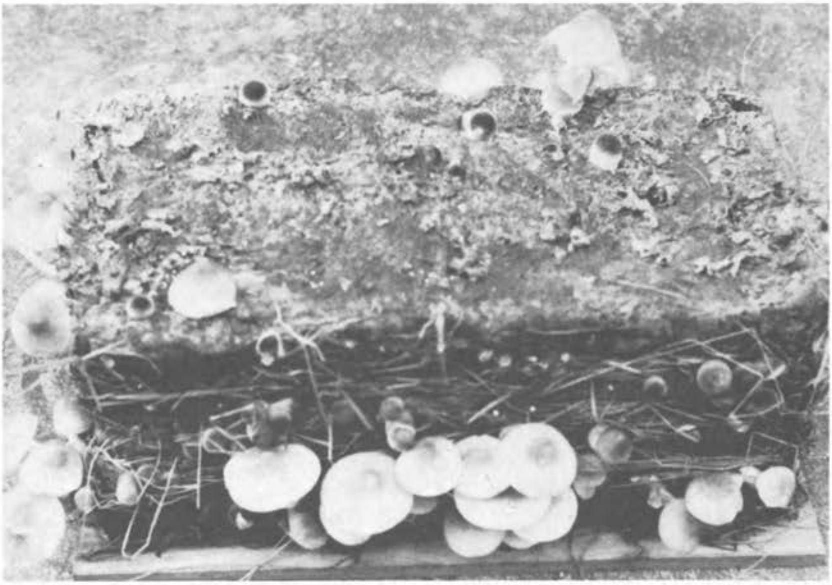

FIGURE 2.4 Straw mushrooms growing well on straw-cotton compost. (S. T. Chang)

mixture of thoroughly wet paper with small amounts of calcium carbonate and wheat bran has been shown by Steinkraus to be an excellent substrate (Figure 2.6).

Low concentrations of sulfite liquor, a waste from paper manufacture, have also been used for *Pleurotus* production in submerged culture. This process can be used both for fungal production and wastewater treatment.

Straw, the simplest, most readily available nutrient base, has been studied to determine the products of its decomposition during *Pleurotus* growth. About 70 percent of the dry weight of the straw is lost as carbon dioxide and water, and about 20 percent remains as compost. Ten percent of the original straw is converted to *Pleurotus* (dry weight); as harvested, about 1 kg of *Pleurotus* is obtained from 1 kg of straw over a period of 2-3 months.

As is the case with substrates from the growth of other mushroom species, the *Pleurotus*-degraded straw can be applied to the soil with beneficial results. The use of this medium has also been examined in ruminant-feeding studies by Zadražil, who found that the wheat straw substrate remaining after the growth of *Pleurotus* had a feed quality equivalent to hay.

Winter, Ear, White Jelly, and Nameko Mushrooms Although each of these species can be grown on sawdust-rice bran mixtures, the commercial practices followed are far from simple. The degree of sophistication and care required for these species is exemplified in the culture of the winter mushroom (Figure

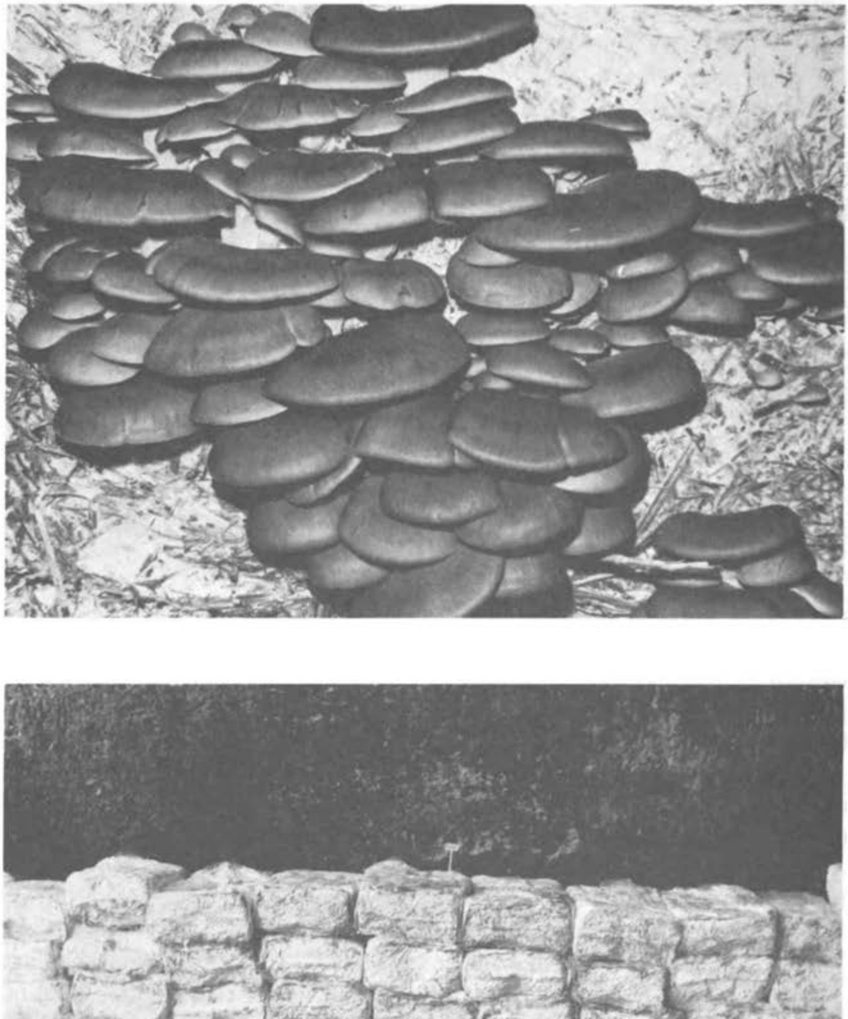

FIGURE 2.5 *Pleurotus ostreatus* cultivated on wheat straw substrate: (top) fruiting bodies; (bottom) a blockwall before fructification. (F. Zadražil)

FIGURE 2.6 Oyster mushrooms grown successfully on shredded paper. (K. Steinkraus)

FIGURE 2.7 *Flammulina velutipes* cultivated on wheat straw substrate. (F. Zadražil)

2.7) in Japan. The sawdust from selected broadleafed trees is often stored for 6-12 months to develop the proper consistency; after this medium is mixed with rice bran and the moisture content adjusted, polypropylene bottles are partially filled with the mixture, capped, and autoclaved. After sterilization the bottles are cooled and inoculated with spawn; during the periods of spawn running and fruiting through harvest (45-55 days), both the temperature and humidity levels are changed four times to optimize growth at various stages of development.

Stropharia rugoso-annulata Cultivation of this European species (Figure 2.8) utilizes straw and relatively simple procedures. Although reported yields are variable (3-17 kg/m^2), its resistance to disease, pests, and environmental change is encouraging.

The culture method developed by Zadražil and Schliemann requires clean, fresh, moist straw as a substrate. No additives have proved to be beneficial. After inoculation the beds are covered with moist burlap sacks or newspaper and compressed with weighted boards. When surface growth appears (3-5 weeks), this covering is replaced with a layer of moist humic soil. The first crop can be harvested in another 4 weeks and successive crops continue for 6-8 weeks. Total yields are about 600 g per kg of dry straw.

Coprinus fimetarius The fleeting life cycle of most members of the genus *Coprinus* precludes their practical cultivation. In work with *C. fimetarius* (Figure 2.9), however, Kurtzman has found that this species can be stored at least 3 days with good refrigeration or canned or dried for longer storage.

This characteristic combined with swift growth over a broad temperature range and modest substrate requirements make *C. fimetarius* an attractive candidate for broader use. Starting with dry straw, mushrooms can be harvested in 9 days or less. Although a high relative humidity (about 90 percent) must be maintained, temperature control is not critical; *C. fimetarius* can be grown from about 20°C to 40°C.

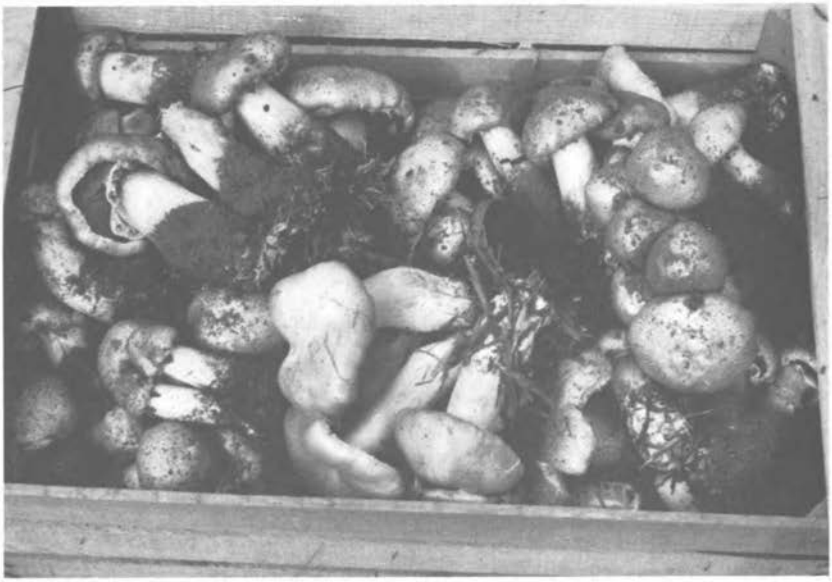

FIGURE 2.8 Harvested *Stropharia rugoso-annulata*. (F. Zadražil and J. Schliemann)

FIGURE 2.9 Starting with dry straw, *Coprinus fimetarius* can be harvested in 9 days. (R. Kurtzman)

In Kurtzman's cultivation studies, fresh dry straw is immersed in 3-4 times its weight of hot (80°C) water. Calcium nitrate, at about 5 percent of the dry straw weight, is dissolved in the water as a nitrogen source. The straw is then packed in beds, allowed to cool to 40°C, and inoculated. The straw is covered with a plastic sheet until the first appearance of surface growth–about 3-7 days. About 2 days after surface growth begins, mature mushrooms can be harvested. Successive crops can be obtained for about 20 days with the total yield (fresh weight) equal to about 60 percent of the dry weight of the straw.

Yeasts

A variety of waste substrates have been utilized for the growth of food yeast, including whey, molasses, wood hydrolysates, starch waste, and sulfite liquor.

The species most commonly used in the production of food-grade yeast are *Torulopsis utilis* (Torula yeast), *Saccharomyces cerevisiae* (baker's yeast), and *S. fragilis. T. utilis* was produced from wood hydrolysates for food and feed in Germany during World War II. *T. utilis* is currently produced from paper mill waste sulfite liquor by Boise-Cascade in Salem, Oregon.

This plant produces about 4,000 tons of yeast per year from a waste that would otherwise be discarded.

In Thailand, pollution caused by cassava factories is particularly acute. In examining waste treatment alternatives, the most desirable solution was one that could provide by-product recovery to offset treatment costs. In batch fermentation experiments it was demonstrated that *T. utilis* could achieve production of yeast solids amounting to about 40 percent of the total solids in the wastewater.

Food-grade *S. fragilis* yeast is produced from cheese whey. In the United States a 4,500-tons-per-year plant is operated by Amber Laboratories in Juneau, Wisconsin. *S. cerevisiae* is commonly grown on molasses.

Each of these yeasts can be separated from its growth medium by multistage centrifugation and drying. The United States Food and Drug Administration allows their use in foods provided that their folic acid content does not exceed 0.04 mg/g. The use of dried yeast in foods is generally limited to flavor enhancement and B-vitamin supplementation. Yeast hydrolysates are also used as condiments for starchy foods.

Bacteria

A number of bacterial species have potential use as food. Their protein content can be quite high, up to 80 percent in some species. Their growth rate is rapid compared with some other microorganisms. *E. coli*, for example, multiplies about 20 times as fast as algae. In terms of quality, bacteria usually contain all the essential amino acids and substantial amounts of vitamins.

In his review, Litchfield describes a wide range of bacterial species that have been considered for food or feed production. Since many of these processes utilized petroleum fractions or petrochemicals as substrates, the economic impetus for their implementation has decreased sharply. Species utlizing agricultural, agroindustrial, or chemical wastes were slated primarily for feed production.

The major problems in the use of bacteria as food are toxicity (or the high cost of determining lack of toxicity), digestibility, high nucleic acid content, and cell recovery from dilute (10-20 g dry weight per liter) liquid substrates. Bacterial cell densities are close to the density of water; thus centrifugal separation is expensive, but it is the only viable method because of the cell size (1-2 μm).

Limitations

The following general limitations must be considered in the utilization of waste material for food.

Among various groups of people, certain foods are unacceptable. A wide variety of species of mushrooms are eaten by Asians and Eastern Europeans, whereas many in western countries accept only the common white mushroom, considering all others to be inedible or poisonous.

Many crops are seasonal, and surpluses during peak periods are not uncommon. Facilities for storage of wastes and for handling more than one kind of waste might be required. The utilization processes may be uneconomical because of the equipment or buildings required or the cost of labor.

Toxins, especially the aflatoxins, produced by certain species of microorganisms may be carcinogenic. The crops most often contaminated with aflatoxins are maize, cottonseed, groundnuts (peanuts), tree nuts, and milk from cows that consume aflatoxin-containing feed.

It has been reported that in oncom preparation using *N. sitophila* as the fermenting organism, about 50 percent of the aflatoxin in the peanut presscake is destroyed during fermentation; *R. oligosporus* destroyed about 60 percent of the aflatoxin. Thus, relying on fermenting organisms to control aflatoxins will provide a real advantage only if the aflatoxin content of the raw material is low; otherwise, remaining aflatoxins will still exceed the permitted levels (30 ppm) suggested by the World Health Organization.

In some commodities the chemical nature of the waste material–for example, the high ash content of chicken manure and the high silica content of rice hulls and straw–may be unsuitable.

Recycling some wastes may result in the concentration of pesticides or of medicinals used to promote animal growth or to control animal diseases. When wastes come from industrial centers, they may contain undesirable amounts of heavy metals such as mercury, cadmium, or lead, or toxic organic compounds such as chlorinated biphenyls.

Fast-growing cells have such a high nucleic acid content that, when used as a protein source, they can raise serum and uric acid levels to unacceptable limits. Even yeasts and bacteria processed to reduce their nucleic acid content may cause gastrointestinal or cutaneous reactions in humans. To this end, the Protein Advisory Group of the United Nations has developed guidelines for the testing of novel protein sources and supplementary foods prior to human use.

Research Needs

Although research on various aspects of food production from wastes has been carried out in many countries, there is still a need to improve safety, acceptability, and marketing practices and to identify essential microorganisms, processing methods, and changes in the biochemical and nutritional characteristics of the substrates occurring during fermentation.

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3 Feed from Wastes

The conversion of wastes directly to human food presents a number of problems when the source of the waste is not inherently food grade. These problems may be circumvented to a large degree by the use or conversion of wastes to feed domestic animals. By this means, man's nutritional resources can be vastly expanded.

In producing food crops, by-products or residues suitable for conversion to animal feed equal or greatly exceed the edible food components. The proportion of such residues to the food obtained for human consumption is approximately 1.5-1 for roots and tubers, 2-1 for cereal grains, 6-1 for oilseeds, and 10-1 for sugar crops.

Thus the quantities of these residues are large. Recent estimates indicate cereal straw production in Asia is more than 600 million tons. Africa and Latin America produce more than 200 million tons of straw. The residues from cassava, banana, citrus, and coffee in these three regions were estimated to be 124 million tons, plus another 83 million tons of sugarcane residues. Although most of the manure from the 3.5 million livestock in Africa, Asia, and Latin America is probably used for fuel or compost, alternative uses in feed preparation are possible.

In any region, food production utilizing wastes can provide economies; for example, where food and feed are in short supply, waste utilization conserves nutrients that have already been produced or grown. The reduction of postharvest food losses–the losses to which foodstuffs are liable between harvest and consumption because of improper drying, processing, or storage, and the depredations of rodents, insects, and birds–is a problem closely related to waste utilization and has been treated in a companion report: *Postharvest Food Losses in Developing Countries.**

Most feedstuffs receive some processing before being fed to animals. Processes commonly used include chopping, grinding, mixing, and baling. Grazed or browsed herbage is the only feed consumed without processing. Since in most areas of the world animals cannot be grazed continuously, some stored and processed feed is usually needed for part of the year. Processing of organic materials for animal feed, therefore, is a common practice.

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*National Academy of Sciences, 1978.

The nutritive value of organic wastes and residues can be enhanced by physical, chemical, and microbial processing. Typical materials that can be treated include cereal straws and stalks, bagasse, wood residues, animal wastes, and vegetable- and fruit-processing wastes.

Cellulose and hemicellulose in the plant cell wall are the most abundant carbohydrates in the world. Chemically, they consist of glucose and other sugar units linked in long chains. While most animals do not produce enzymes capable of digesting cellulose and hemicellulose, ruminant animals (cattle, buffalo, sheep, and goats) have digestive tracts modified to provide for the fermentation of these carbohydrates by microorganisms. Even ruminants, however, cannot completely digest cellulose and hemicellulose because in the plant cell wall they are physically and chemically associated with the indigestible lignin and silica. Therefore, processing to rupture the cell wall can greatly improve the feeding value of straws, stovers, and similar cellulosic by-products.

Techniques for utilizing crop residues, animal manures, and agroindustrial wastes for feed production will be considered in turn. The production of algae from animal and human wastes for use as feed will also be discussed.

Crop Residues

Crop residues have been used as livestock feed since ancient times. Only in recent times have grain surpluses in Europe and North America given rise to agriculture systems in which straw is not used for feeding. In Asia and Africa straw remains the staple feed for most livestock. Even in Europe and North America the era of surplus grain may be drawing to a close, and more reliance will again be placed on straw as a feed.

Alkali Treatment

It has been known for nearly a century that the alkali treatment of straw can increase its digestibility. The earliest methods of treatment, developed in Germany, involved pressure cooking straw in dilute sodium hydroxide solutions, followed by washing with clean water to remove unreacted alkali. The sodium hydroxide dissolved the lignin and silica, hydrolyzed ester linkages among cell wall constituents, and caused the cellulose to swell, all of which enhanced digestibility. Later, Beckmann replaced pressure cooking by simple cold water soaking to reduce costs. By this Beckmann process, which was used in Europe intermittently from 1921 onward, the digestibility of straw increased from about 45 to about 70 percent. Its popularity was still limited by treatment costs and because 25 percent of the original dry matter, including most of the hemicellulose, was lost. Other drawbacks were environmental pollution and high water requirements. In a still simpler method, a 4-5 percent aqueous solution of sodium hydroxide is sprayed on the straw and fed directly to animals after a 24-hour "curing period" (Figure 3.1). In this method the disadvantages of the Beckmann process are largely overcome, but it is less effective–digestibility increases by only 10-15 percentage units.

Sodium hydroxide treatment has been commercialized in Europe to produce treated straw pellets that can be more readily stored and transported. However, the market is very limited because of the relatively high costs of processing and transportation, and recent increases in the price of sodium hydroxide have made its use in treating straw less economic by any method.

Other, cheaper alkalis can also be used. Calcium hydroxide is almost as effective as sodium hydroxide if the treated straw is permitted to "cure" in a covered stack or in a silo for several months. Methods using calcium hydroxide in a small-scale modified Beckmann system, in which work water is recycled, are being investigated and appear to be promising.

Ammonia is also effective in treating straw. Digestibility is increased by 10-15 percentage units, and nitrogen content is increased by about 1 percentage unit (from about 3 to 4 percent of the straw on a dry-matter basis). The Norwegian method, now widely used in Europe, uses anhydrous ammonia injected into stacks of baled straw covered with a polythene sheet (Figure 3.2). Reaction time is about 2 months, and 3-4 kg of ammonia are used for each 100 kg of straw. Alternatively, urea can be used as a source of ammonia for straw treatment (Figure 3.3): 4 kg are dissolved in 100 liters of water and sprinkled on each 100 kg of straw as it is stacked. In Bangladesh, Ahmed and Delberg have found that straw with up to 50 percent moisture can be preserved by using this method. The preservation of high-moisture straw can be vital during monsoon harvest. The stack does not have to be covered with a polythene sheet to ensure good treatment but only with a thatch to keep out rainwater. Recent research in India and Bangladesh has shown that cattle urine can also be used as a source of ammonia to treat straw.

Alkali-treated straw can replace hay and silage in the diet if the difference in protein content between the treated straw and the hay or silage is compensated by an appropriate protein supplement or by urea. When using treated straw, however, it must be realized that individual lots will vary widely in digestibility, as do individual lots of hay and silage. The initial digestibility of straw varies between 35 and 55 percent. Treatment increases this by 10 to 15 percentage units depending upon the method used, with the extent of increase among straws more or less independent of initial digestibility. Factors that affect initial digestibility include species, time of harvest, and method of handling.

The treatment of the straw fed to bovines can about double the rates of weight gain and milk yield if protein in the diet is adequate. Treatment with urea or ammonia provides adequate additional protein. However, with sodium

FIGURE 3.1 Daily spray treatment of straw. This is the easiest method but is less effective than other methods of NaOH treatment. (FAO)

FIGURE 3.2 A stack of straw bales that has been treated with anhydrous ammonia. Note the careful sealing around the base. (F. Sundstol)

FIGURE 3.3 Rice straw can be treated with a urea solution in a small container to improve digestibility. (M. Saidullah)

hydroxide or calcium hydroxide a protein supplement will usually be needed. A urea solution applied to the straw at the time of feeding (1 percent of the weight of dry straw) will provide the additional protein through microbial synthesis in the rumen.

Bagasse can also be treated with alkali to increase its digestibility. Owing to its much lower initial digestibility, it has not proved economical as a feed either treated or untreated except during famine periods. Moreover, in many countries it is used as fuel in the sugar factories.

Attempts have also been made to improve the digestibility of rice hulls, but with little success. Digestibility even after alkali treatment is only half that of treated straw.

Physical Processing of Crop Residues

Grinding is a valuable means of improving the use of many plant products for ruminant feed because it exposes an increased surface area to the attack of rumen microorganisms. Grinding crop residues improves the efficiency of utilization, especially by growing and lactating animals, primarily through increasing their intake. Ground high-quality grass or legume forage can be used to a limited extent in swine diets, especially for breeding animals, because of the relatively high proportions of soluble sugar to cellulose in these crops.

Pressure cooking sawdust and ground whole trees has been found by Canadian scientists to increase digestibility markedly, but this process is not commercially viable where there is no surplus of wood or wood processing residues.

Single-Cell Protein Production from Crop Residues

Dilute sulfuric acid, mixed sulfuric and hydrochloric acids, or sulfuric acid with a small amount of nitric acid can be used to hydrolyze the cellulose and hemicellulose of fibrous residues. An example of this treatment process was the production of wood molasses from oak species in Tennessee and Alabama in the early 1940s. An excellent process was developed, and a pilot plant was built and operated. Although the molasses product proved to be almost equal to cane molasses in feeding value, the process was not economically competitive and was discontinued. In recent years, further experimentation has been done with processes in which the sugar is subsequently used for single-cell protein (SCP) production. In the United States, several processes for converting wood waste and other agricultural crop residues to animal feed have been developed as far as the pilot plant stage. In some processes, the SCP is not separated from the original substrate (that is, crop residue). Digestibility of this product is about the same as that of the original straw—the enhancement in feeding value is only in terms of the protein synthesized from the microbial fermentation. Whether or not this method of producing additional protein for animal feeding can be economically competitive is yet to be determined.

Han et al. developed a process to produce an animal feed protein supplement from bagasse and rice straw by alkali pretreatment followed by a fermentation with a symbiotic pair of microorganisms, *Cellulomonas* sp. and *Alcaligenes* sp. The first organism degrades the cellulose and the second grows on the degradation product and increases the cell mass. The microbial cells contain about 50 percent protein, which has an amino acid profile similar to that of soybeans.

Barley straw fermented with *Trichoderma viride* produced a mixture of mycelium and unfermented straw containing 18-24 percent protein and 30 percent lignin. The overall rate of protein and cellulose production was increased when barley straw was fermented with a mixed culture of *Trichoderma viride* and *Saccharomyces cerevisiae* or *Candida utilis*.

The Korean Institute of Science and Technology has also developed a process to increase the feed value of rice straw. Rice straw is chopped and treated with 0.25 percent calcium hydroxide, heated, and then neutralized with phosphoric acid. *Aspergillus* sp., grown on steamed wheat bran, is mixed with the chemically pretreated rice straw in the ratio of 1:5, and fermented anaerobically at 45°C for 3-4 days. These conditions allow the enzymes formed to act on the mixture, but they inhibit mold growth. The final product contained about 8 percent crude protein and had an *in vitro* rumen digestibility of about 43 percent. Unfermented rice straw contained about 5 percent protein and had an *in vitro* rumen digestibility of about 47 percent. When the product was fed to milking cows, it was palatable and could substitute for up to 10 percent of the grain in a complete ration.

These SCP processes would be feasible only in large-scale, centrally located commercial plants because of special handling and equipment requirements.

Animal Manures

In the system of livestock husbandry developed in Europe and North America over the past half century, large concentrations of manures are produced on feedlots remote from farms. Ways have therefore been developed of recycling these as animal feed where they are produced. Ensilage can provide an effective, low-cost means of conserving nutrients in animal excreta (cattle, swine, and poultry) for refeeding. These organic wastes are valuable animal feeds, especially for ruminants, and may be more valuable as animal feed than as fertilizer.

Day has noted that on an annual basis a laying hen produces about twice as much crude protein as manure than in the form of eggs. Smith and Wheeler have concluded that the economic value of excreta as a feed ingredient for some ruminants is 3-10 times greater than its value as fertilizer.

Ensilage is effective in making animal wastes safe for refeeding. When properly treated, ensiled animal wastes undergo lactic acid fermentation, and if the product is held for 10 days in a silo prior to feeding, pathogenic bacteria such as salmonellae, parasitic nematodes, and coccidia are practically eliminated. Spore-forming bacteria, while not destroyed, do not proliferate; these bacteria are usually not harmful. Moreover, ensiled animal wastes look and smell better than untreated excreta.

Animal wastes are conserved for silage use in a fresh, uncontaminated state, without adding water, and should be mixed with sufficient dry fermentable feed to increase the dry matter content to about 55 percent. The silo may be a box, a plastic bag, a trench, or a commercial airtight silo. The blended product is packed tightly into the silo to exclude oxygen and provide the minimum exposed surface area. For open-topped silos, spraying the exposed top surface with formic acid or formaldehyde will help control fungal growth. If surface mold growth occurs, the moldy layer should be removed before feeding the silage, since it may be toxic. It can, however, be used as fertilizer.

A suitable ratio for blending cattle and swine wastes with dry feed is 60 parts animal waste to 40 parts feed. Poultry litter can be used as a mixing ingredient to conserve swine and cattle excreta. In this system a workable formula is 60 parts swine or cattle waste, 20 parts air-dried poultry litter, and

20 parts ground grain, hay, or crop residue. This type of formula is generally known as "wastelage." Wastelage may constitute the entire ration for breeding cattle. Enriched with a higher energy feed, it can be fed to growing and lactating animals. Wastelage is usually deficient in vitamin A, so this nutrient must be supplied. There is no significant buildup of indigestible inorganic residue, so recycling in this fashion can be continuous. One donor animal housed in confinement provides enough manure to produce feed for about two animals. Thus only some of the cattle need to be confined.

Other manure ensilage processes have included cassava-poultry litter in Malaysia, molasses-manure in Cuba, and molasses combined with maize residues, cattle manure, and urea in Mexico.

The conversion of excreta to animal feed can also be done aerobically. Swine and poultry droppings are collected in an aerated sump, and portions of the wastes are synthesized into microbial protein by the microorganisms in such systems. These microbially enhanced wastes can be fed to animals as part of their drinking water (Figure 3.4).

Significant increases in the amino acid fraction of dry matter in aerobically treated swine manure have been found. In feeding trials conducted by Harmon, feeder pigs receiving aerobically processed swine manure grew more rapidly and efficiently than pigs whose diet did not contain this material.

In a 3-year study by Martin, aerobically treated poultry manure was fed to the poultry that produced the manure. The egg production by the hens receiving this material exceeded that of a control group by 2-3 percent. No significant differences in body weight, mortality, or egg weight were observed.

Agroindustrial Wastes

Many agroindustrial wastes, particularly those derived from food processing, are actually or potentially useful as animal feed. With many of these wastes, there is also a need to reduce their potential for pollution.

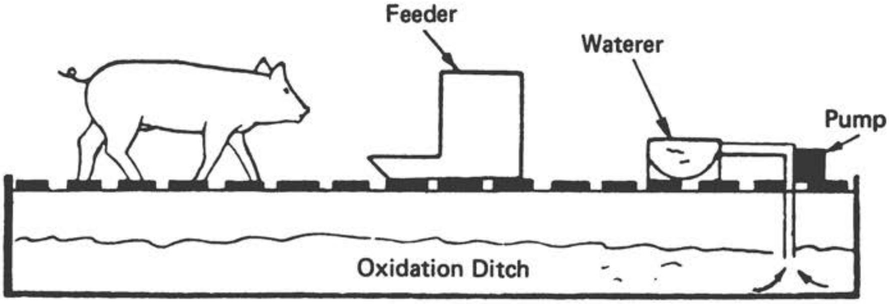

FIGURE 3.4 Swine wastes are collected in an aerated sump, enhanced in protein content through microbial action, and refed as part of their drinking water. (FAO)

A number of these wastes have been used directly as animal feeds. These include pineapple pulp, bagasse, overripe bananas, ramie, coffee wastes, mustard wastes, citrus pulp, grapeseed meal, and olive cake. They have been fed to ruminants or pigs at levels of 5-20 percent with no adverse effects (Figure 3.5).

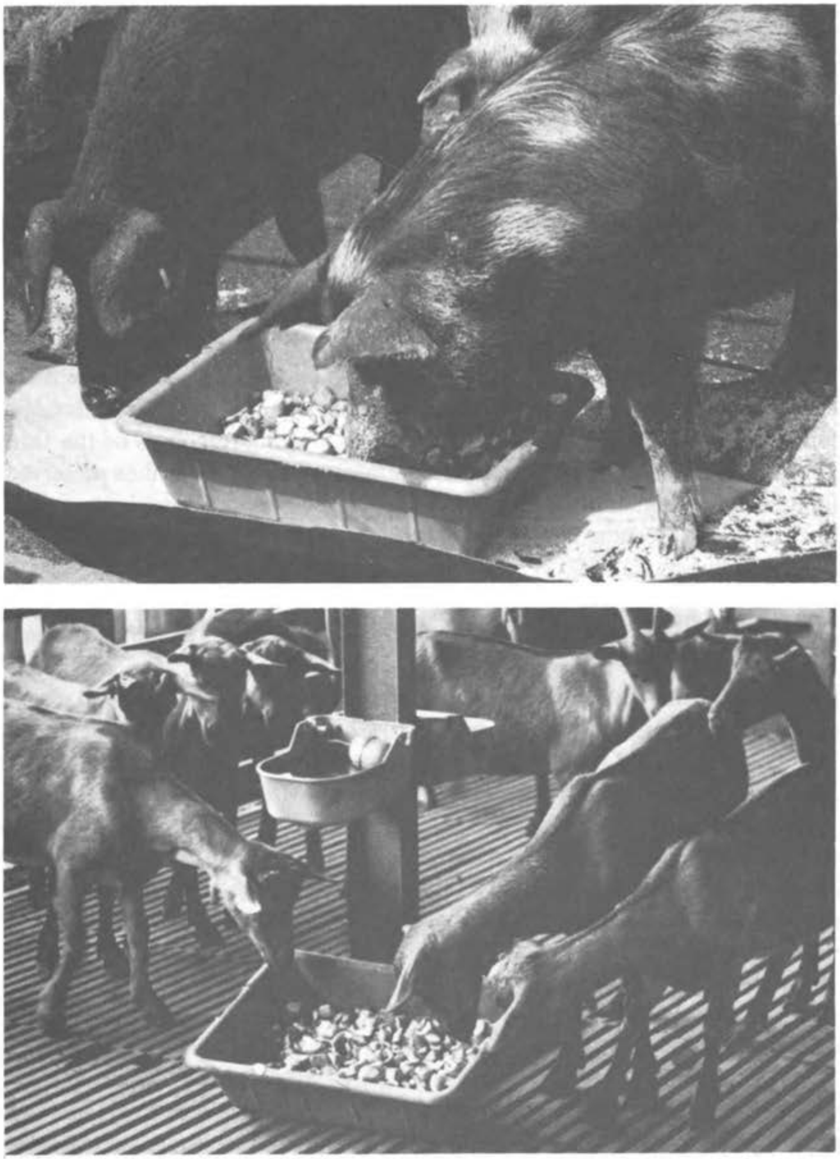

FIGURE 3.5 Pigs and goats consuming unmarketable bananas. (FAO)

Food-processing wastes are especially well suited for microbial conversion to animal feed, because they often contain a balanced concentration of organic and inorganic nutrients. In general, there are no toxic materials present. One problem is the seasonal availability of these wastes. Significant capital expenditure for a processing plant is usually based on year-round operation.

The Pekilo process, developed in Finland, is continuous fermentation in which protein is manufactured by cultivating the fibrous fungus *Paecilomyces varioti* on carbohydrate wastes. Using spent sulphite liquor from paper mills, a new plant in Jämsänkoski, Finland, can produce 10,000 tons of biomass annually. The dried product, containing 52-57 percent crude protein, is sold to feed compounding mills.

Fish offal may be sun dried or may also be conserved as silage with the addition of fermentable carbohydrate. An example of the latter process is the sugarcane-fish-manure system developed at the Caribbean Industrial Research Institute, St. Augustine, Trinidad, by which raw waste fish and raw cattle manure are mixed with sufficient chopped cane to increase the C:N ratio to about 20:1 and packed in a bed. The material undergoes a rapid lactic fermentation, and the pH drops to 4.2 within 24 hours. This prevents the alcoholic fermentation of the sugars in the sugarcane and the proteolysis of the fish. The protein of the fish and the carbohydrates of the cane are thus preserved for future feeding. The use of other waste proteinaceous materials to replace the fish, such as legume wastes, distillery slops, and other animal wastes might be tried in this system. In any lactic fermentation it is important that adequate carbohydrates are present to allow the fermentation to proceed.

Upgrading is normally associated with the conversion of carbohydrate carbon and inexpensive nitrogen to protein, producing a protein-enriched material of greater value. The fermentation of coffee pulp, which has been developed at the Central American Research Institute for Industry, Guatemala City, Guatemala, and the protein enrichment of cassava waste are examples of upgrading. In this SCP process, the SCP is not isolated as a pure material but is left in the mash.

Hot air dehydration has been used to conserve fruit and vegetable cannery by-products as well as brewery, distillery, and sugar beet wastes, but high fuel costs are making this practice uneconomical. The more appropriate way to use such wastes is to feed them fresh near the factory.

Algae

The uncontrolled discharge of human and animal wastes can cause environmental pollution and threaten public health. The need to render these wastes and wastewater harmless is obvious, but the cost of treatment is often high.

Conventional waste treatment techniques, such as activated sludge plants, often require large investments and large amounts of energy, making them increasingly less attractive. Using wastewater productively while achieving a degree of treatment is therefore of considerable interest the world over.

Researchers in the United States, Australia, the Philippines, Israel, India, Germany, and Singapore have shown that human and animal wastewaters are excellent substrates for the cultivation of algae. These microscopic planktonic plants are capable of photosynthesis in the presence of sunlight and release oxygen. The oxygen supports bacterial populations that break down the organic matter in wastewater. This symbiotic action renders the organic matter innocuous and, at the same time, converts the waste into nutrients for algae. The algae, containing 45-65 percent crude protein, can be harvested and processed for animal feed. The water then has a much reduced organic content with biochemical oxygen demand (BOD) ranging from 30 to 80 mg/liter, and can be discharged with minimal environmental impact. One system of treating wastewater through the growth of algae is referred to as the high-rate pond system, so called because it is designed to maximize the use of oxygen produced by the algae. The potential productivity of algal protein from the high-rate pond system is impressive, as is shown in Table 3.1.

TABLE 3.1 Estimated Protein Productivity of Algae Compared to Conventional Crops

	Protein Yield kg/ha/year	
Crop	Typical	Highest Reported
Soybean	303	1,170
Corn	179	805
Groundnuts	229	598
Rice	71	630
Algae	–	82,000

High-rate pond systems are characterized by depths ranging from 200 to 400 mm. Shallow depths aid in the penetration of light and optimize the efficiency of solar conversion. These ponds require simple construction without the need for concrete bottoms. They can be below ground level, above ground level, using low-cost asbestos sheets as in Singapore for pig waste treatment (Figure 3.6), or even built into the roof of animal housing units as demonstrated in the Philippines. Mixing at low speed to keep the algae in suspension and in good contact with the nutrients from the wastewater is required. This can be accomplished with pumps, windmills, or paddle-wheel mixers (Figure 3.7).

The organic loading rates in high-rate ponds are often based on the amount

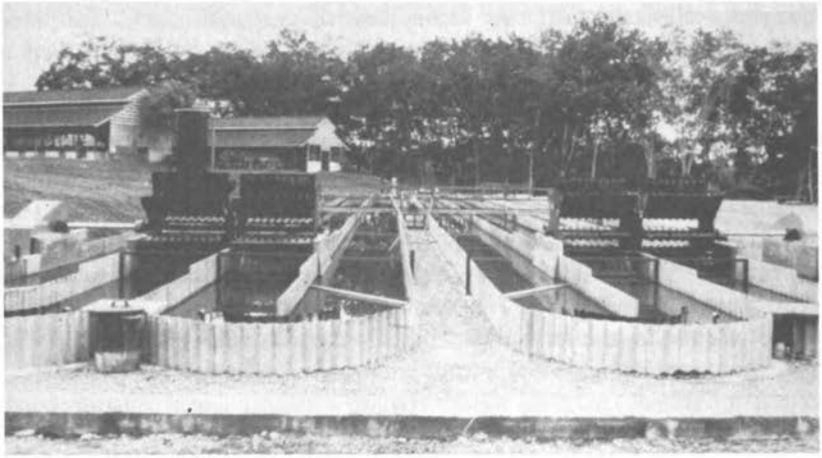

FIGURE 3.6 Pilot-scale (125 m^2) high-rate algae production ponds utilizing piggery wastewater. (IDRC/UNDP/FAO/PPD Singapore)

of BOD loaded, and range from 200–400 kg/BOD/ha, depending on the amount of solar radiation. Concentration of wastewaters loaded into high-rate ponds have ranged from 300 mg/liter for municipal wastewater to 900 mg/liter of dissolved oxygen as the result of photosynthesis. This level falls to below 2 mg/liter just before sunrise. Retention time of the wastewater in a high-rate pond is short, ranging from 2–8 days. Normal pH range of high-rate ponds is between 7.5 and 8.5, with the highest pH level reached during peak photosynthetic activity.

The types of algae that grow in high-rate ponds are highly variable, depending on local climatic conditions, wastewater characteristics, and operational factors. Some of those commonly encountered are green algae such as *Chlorella*, *Micractinium*, *Scenedesmus*, *Ankistrodesmus*, and *Crystis* (Figure 3.8). *Oscillatoria*, a filamentous blue-green alga, has also been found in high-rate ponds. The factors affecting algal species dominance in high-rate ponds require investigation. Most high-rate pond operators have experienced sudden shifts in algal species composition as the result of weather or operational changes.

The importance of species dominance lies in its impact on the cost of harvesting. Species such as *Micractinium* and *Scenedesmus*, which are colonial and spine bearing, and *Spirulina* are readily harvested by filtration with fine-mesh fabrics. *Oscillatoria* can be harvested readily by microstraining. However, *Chlorella*, a small coccoid, single-celled alga, is difficult to harvest.

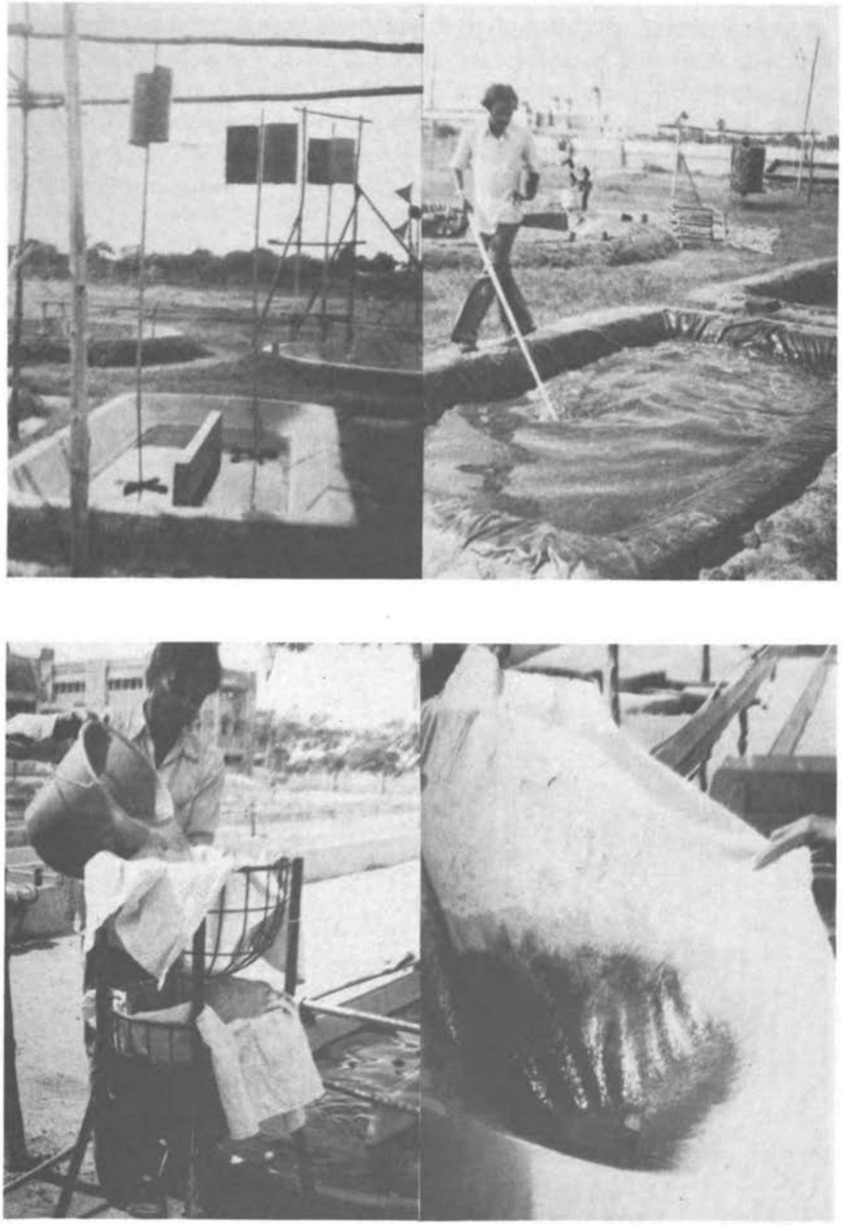

FIGURE 3.7 *Spirulina* cultures in India are stirred (1) with small windmills or (2) manually. Harvest is by filtration through a fine-mesh cloth (3 and 4). (F. Majid)

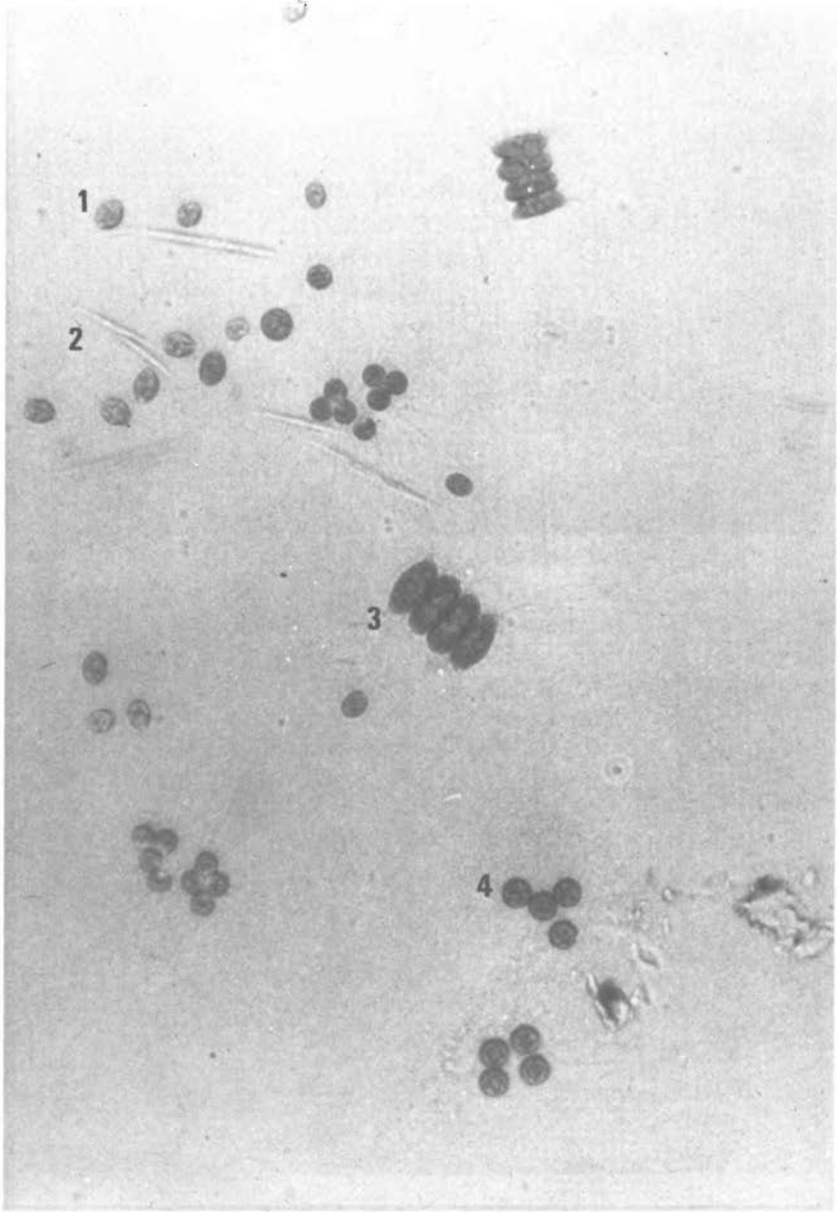

FIGURE 3.8 Types of algae growing in pilot ponds (magnified 200 times): (1) *Crystis*, (2) *Ankistrodesmus*, (3) *Scenedesmus*, (4) *Micractinium*. (IDRC/UNDP/FAO/PPD Singapore)

Predators in high-rate ponds are another problem. In Singapore the cladoceran *Moina* (Figure 3.9) is an intermittent predator. Elsewhere, *Daphne* and rotifers are common algal predators. Such predators can rapidly decimate the algal population and adversely affect the quality of the discharge water by adding more soluble BOD. Hence control of these predators is an essential part of pond management. One successful technique in Singapore has been to bring the pond pH to 9.5 with lime when *Moina* becomes troublesome.

There is currently no single process that will economically harvest the wide variety of algae found in thin suspension (0.04–0.06 percent solids) in high-

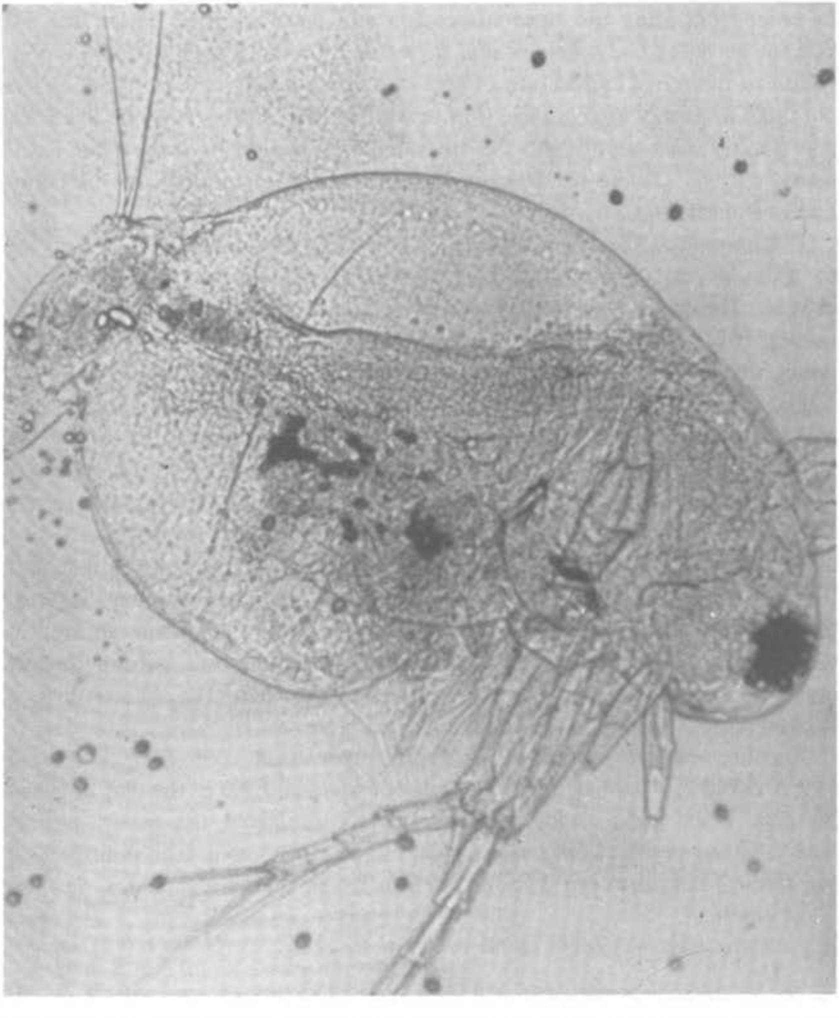

FIGURE 3.9 *Moina* sp: predator of algae in high-rate ponds. (IDRC/UNDP/FAO/PPD Singapore)

rate ponds. Most developmental efforts are in this direction. Israeli workers are studying flocculation of algae with alum and subsequent removal by air flotation. In Singapore, research on a pilot-scale project with 2,900 m^2 of high-rate ponds involves continuous filtration using commercially available fine-weave filter fabrics. This group is also evaluating a process in which the alum used to flocculate algae is recovered by acidification of the algal slurry and recycled. The result can be both reduction of residual alum in the algae and lower cost.

Researchers in the Philippines and the University of California, Berkeley, are evaluating a natural process of autoflocculation in algae culture as a means of preconcentrating the algae suspension and have achieved better than 90 percent algae recovery. Harvesting, therefore, may no longer be a major constraint to the broad application of high-rate pond technology. Considering the potential impact of algal protein production (56–82 tons/ha/year) on livestock and poultry feed supply and the environmental benefit of wastewater treatment, current efforts to develop algae-harvesting technology are certainly timely and essential.

Postharvest processing of algae grown on waste has ranged from sun drying to drum drying. Sun drying, particularly in arid climates, is a low-energy process. However, the digestibility of sun-dried algae is low when fed to monogastric animals such as pigs and poultry. If the algae are fed to ruminants, digestibility is not a constraint. Drum drying, which ruptures the cell walls, produces sterile algal powders or flakes, which are easily digested by pigs and poultry. Although it is a high-energy process, much of the energy can be supplied by digesting the solids obtained from pretreatment of wastewater to produce methane. This is being investigated in the Singapore project. Drum-dried algae with a 6–8 percent moisture content have excellent keeping qualities and can be treated like any other conventional protein supplement (for example, soybean meal) for the purpose of feed compounding. Alternatively, harvested algal slurry can be cooked, preferably by steam, and fed in wet forms to pigs. Cooking requires less energy than drying, but the product must be used immediately, since it has poor stability. The digestibility of cooked algae is as high as that of drum-dried algae.

Feeding trials conducted in Singapore with steam-cooked algae showed that it could replace half of the 16 percent soybean meal in the diet of growing pigs. When algae totally replaced the soybean meal, the growth performance of the pigs was only slightly depressed. Algae use in fish, poultry, and pig feeding has also been demonstrated in Israel, the United States, and the Philippines.

Limitations

In the United States, the Food and Drug Administration has expressed concern over potential health hazards that may result from using animal manures in feeds. The main concern is the possible contamination of manures by pathogens, antibiotics, pesticides, hormones, or other chemicals.

Although algae production from human and animal wastes seems promising, the technology is not yet fully developed. Constraints other than harvesting include changes in algal species composition and algal predators. Training and careful management would be required for successful operation.

For any feed materials, proper handling of the raw materials and products is needed to assure animal and human safety.

Research Needs

The feasibility of waste-to-feed projects depends on the characteristics, availability, and cost of collection and transport of the raw material and the availability of a market for the resultant product. Detailed information about these items is crucial to the success of any waste or residue utilization effort.

There is no one best technical approach. Each situation requires careful evaluation of the most appropriate technology or technologies chosen to achieve the environmental, economic, and social objectives.

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4 Fuels from Wastes

Developing countries rely on wood, dung, straw, and animal and human power to meet most of their basic energy needs. This energy is used almost entirely for the production, processing, and preparation of food. If additional energy sources were more readily available, agricultural output and postharvest processing could be significantly increased.

Fuel wood supplies are dependent on a supporting ecosystem that is being disrupted in many areas by population growth. Where wood resources are overused without replanting, serious soil erosion has resulted, further limiting biomass production.

As a consequence of fuel wood shortage, dung is increasingly being used as fuel instead of being returned to the soil as fertilizer. It has been estimated that 20 percent of India's energy needs are supplied by burning cow dung. Higher-yielding strains of cereal crops that produce less straw reduce the amount of agricultural waste available for use as fuel.

The search for fuel also affects the lifestyle of rural families. Women and children must devote a large portion of their time to gathering fuel at the expense of schooling and other constructive activities.

With rising demand for fuels in developing countries and reduced supplies, economic growth and individual well-being will depend on more efficient use of traditional fuels, better management of natural resources, and widespread substitution of alternative fuels.

The two general approaches available for the conversion of wastes to fuel are biological and thermochemical. Biological methods include the production of biogas and ethanol. Thermochemical methods involve direct combustion; gasification; pyrolysis to oils, char, and gases; and liquefaction to oils.

Biochemical Processes

The production of biogas and alcohol from wastes and residues is gaining greater attention as energy costs increase. These processes are most advantageous when suitable raw materials are available at low or no cost and where some form of waste treatment is obligatory.

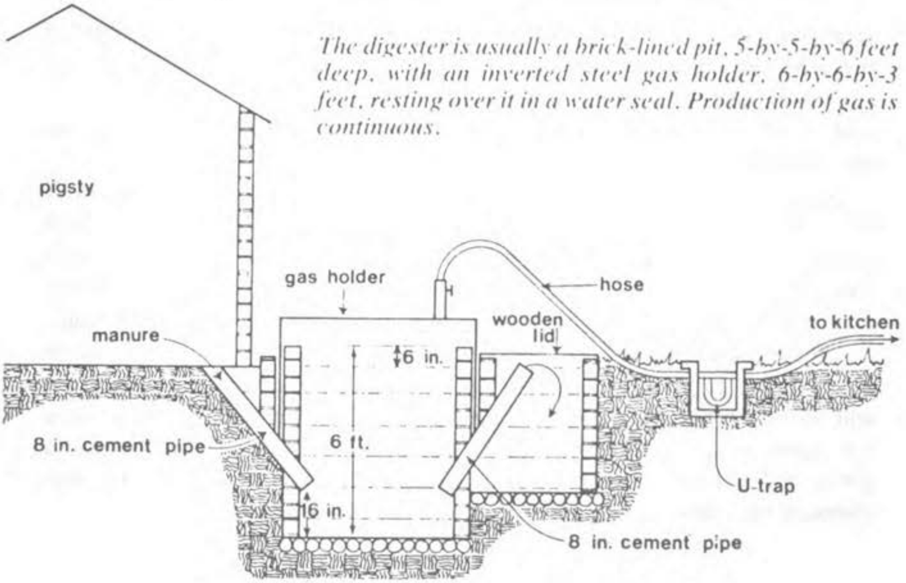
Biogas

The fermentation of wastes to generate methane,* rather than their direct use as fuel or fertilizer, yields a number of benefits, including:

- Producing an energy resource that can be stored and used more efficiently in many applications;
- Creating a stabilized residue that retains the fertilizer value of the original material;
- Reducing fecal pathogens and improving public health; and
- Reducing transfer of plant pathogens from one year's crop residue to the next year's crop.

The process of anaerobic fermentation is a natural one, occurring without man's intervention whenever organic material decomposes out of contact with air. This reaction produces biogas, a mixture of methane, carbon dioxide, and small amounts of other gases. This gas burns readily and can be used directly as fuel for cooking, lighting, or heating, and indirectly to power electrical generators and agricultural equipment.

When this process is used for the conversion of wastes, a slurry of the organic matter is fed to an enclosed digestor. In a typical digestor (Figure 4.1) the gas formed is trapped by an inverted drum covering the surface of the liquid. As gas is produced the drum rises, acting as a gas storage chamber. The



The digester is usually a brick-lined pit, 5-by-5-by-6 feet deep, with an inverted steel gas holder, 6-by-6-by-3 feet, resting over it in a water seal. Production of gas is continuous.

FIGURE 4.1 A typical biogas generator.

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*See also *Methane Generation from Human, Animal, and Agricultural Wastes*, National Academy of Sciences, 1977.

gas can then be drawn off for use as needed.

The most useful constituent of the gas is methane—about 50-65 percent of the mixture. Carbon dioxide makes up most of the remainder, with small amounts of hydrogen sulfide, hydrogen, and nitrogen also present. The factors affecting methane production include the composition and volume of the waste used, the operating temperature, retention time, agitation, and acidity or alkalinity.

The carbon:nitrogen ratio of the waste has a significant effect on the volume of gas produced, a ratio in the range of 20-30:1 being best. This ratio depends on the composition of available wastes. High nitrogen wastes such as human and animal urine can be added to high carbon-content cellulosic wastes to bring the ratio closer to the optimum.

The total volume of wastes that can be processed is a function of digestor size and retention time. The rate of charging the digestor is important: continuous addition of small amounts of material is best, and sporadic additions of variable amounts least desirable. The most practical compromise is daily addition of uniform amounts.

Bacterial activity in the digestor, and therefore gas generation, depends on the temperature of the slurry. Although satisfactory results can be obtained by operating in the range of 20°-40°C, faster decomposition and increased rates of gas formation result when the digestor is run at 40°-60°C. This can be accomplished by burning part of the methane to heat the digestor contents, through solar heating, or by other means. Retention time in the digestor varies with both the temperature of operation and the biodegradability of the substrate. Higher operating temperatures allow greater throughput for a given reactor size. Higher temperatures also tend to reduce pathogen content. Biodegradability varies among wastes and affects both the rate of gas generation and the retention time.

Some agitation in the digestor results from additions to and withdrawals from the fermenting mass. Further deliberate agitation can be beneficial to gas production by dispersing scum layers and breaking down particles to give greater surface area. Incorporation of a stirring mechanism, however, may complicate digestor design and increase the potential for gas leakage.

Digestor bacteria are sensitive to changes in pH; the optimal pH range for methane production is between 7.0 and 7.2, although gas production will proceed when the pH is between 6.6 and 7.6. When the pH drops below 6.6, there is significant inhibition of the methane-producing bacteria, and a pH of 6.2 is toxic to them. Under balanced digestion conditions, the biochemical reactions tend to maintain the pH in the proper range.

Digestor Design In recent years creative modifications have been made in the design of biogas generators. A Nepalese variation on the movable gas storage container provides a more stable center guide and facilitates underground gas transmission (Figure 4.2).

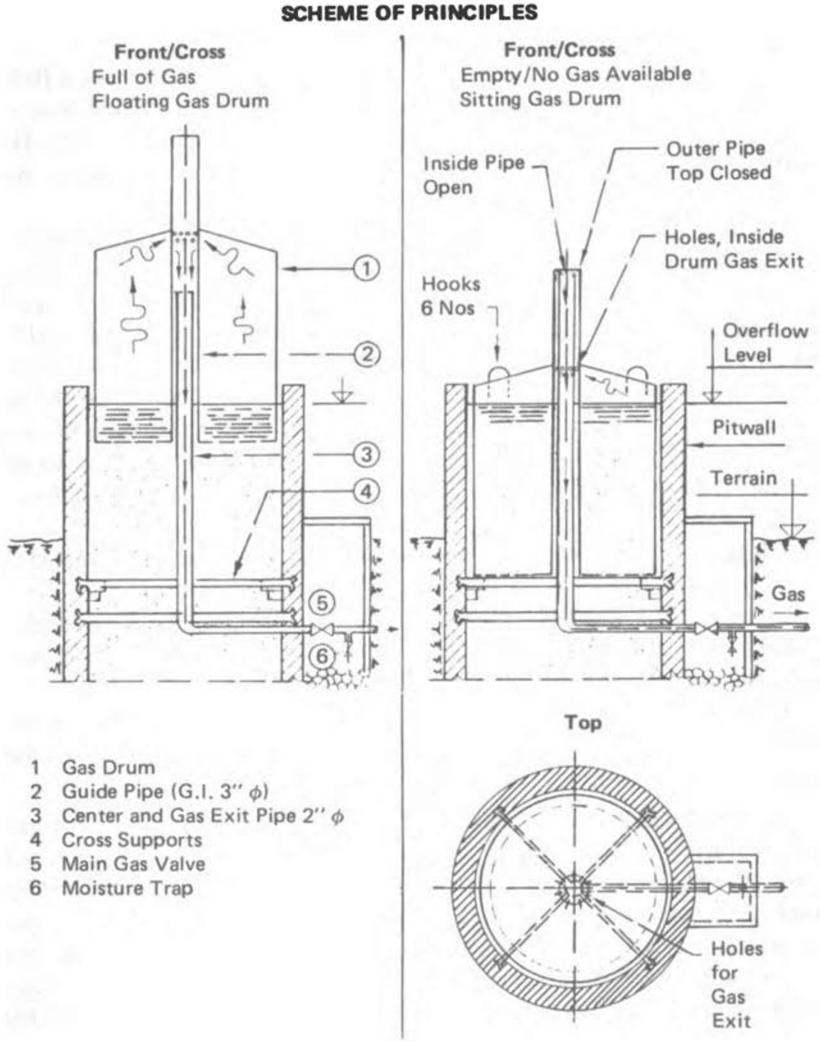


FIGURE 4.2 Movable-top digestor with center guide.

A significant change in design is illustrated in Figures 4.3 and 4.4. These Chinese-designed digestors have fixed tops and rely on self-generated hyrostatic pressure to distribute the gas. As gas collects in the storage area, some of the slurry is forced into a holding tank at a higher level. This level rises and falls with the production and release of gas. A big advantage of these fixed-top generators is that they have a minimum of moving parts and the corrodible metal gas holder is eliminated.

An innovative approach to the design and fabrication of a spherical fixed-top digestor is shown in Figure 4.5. The digestor shell is constructed closer to ground level and then floated and sunk to its final level, below ground. This method could be particularly valuable where the water table is higher than the depth of the final excavation.

The Industrial Technology Research Institute in Taiwan has developed a unique methane generator, comprising a large reinforced plastic bag with an inlet for wastes and outlets for gas and slurry (Figure 4.6). Although installation requires excavation, typical problems of corrosion and leakage in other types of generators are minimized. Moreover, although the biogas generated can be distributed through autogenous pressure, additional weight on the top surface of the bag can be used to increase gas flow. The manufacturer of these units estimates their useful life to be at least 8 years. Four sizes are available to handle the wastes from 10 to 250 pigs and yield 2.5 to 62.5 m^3 of biogas daily.

A British firm manufactures bag-type digestors for above-ground use (Figure 4.7) with capacities of 2.2 m^3 (4.4 m × 1.8 m × 0.6 m) and 13.5 m^3 (15 m × 2.7 m × 1 m). Since no excavation is required for these units, installation is simpler. If necessary, a heat exchanger base can be used to maintain good operating temperatures.

An Australian firm produces a bag-type digestor with panel wall supports (Figure 4.8). In these units, about half the bag is below ground level and half above. Capacities range from about 40 m^3 to 400 m^3.

Mobile Digestors In the Philippines and in the United States, portable methane generators have been used for education and demonstration purposes. The Philippines digestor (Figure 4.9) was developed for the United Nations Environment Programme by the Philippine Center for Appropriate Training and Technology. Its operating characteristics and uses are highlighted in billboard fashion on the sides of the unit. The American digestor (Figure 4.10) was sponsored by the Colorado Energy Research Institute. This 23,000-liter unit has the capacity to convert the fresh manure from 20 dairy cows, 150 pigs, or 2,400 hens to 20-24 m^3 of biogas daily. The design includes a 13 m^2 solar water heater to help maintain the digester temperature near 40°C. Both of these units have been found to be effective tools for establishing technical and economic feasibility and for evaluating locally available wastes for their performance in biogas generation.

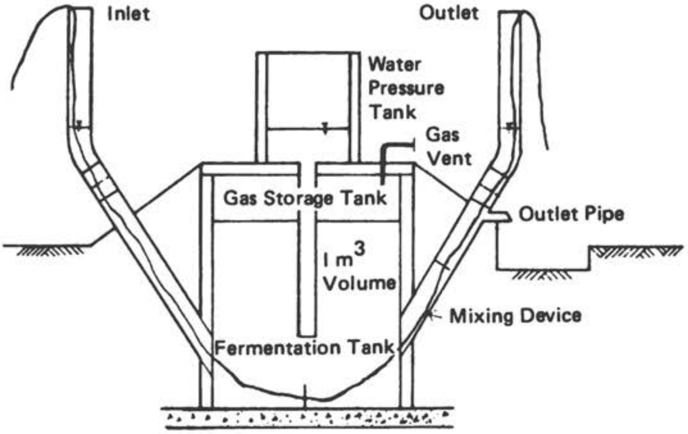
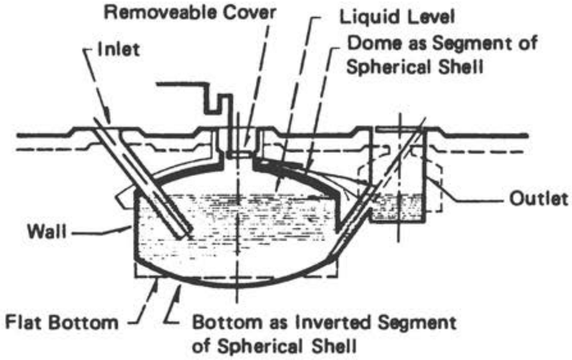


FIGURE 4.3 Fixed-top digestor (note unique mixing device).



m3	h (mm)
6-10	150
50	300
100	400

FIGURE 4.4 Fixed-top digestor with dish-shaped bottom.

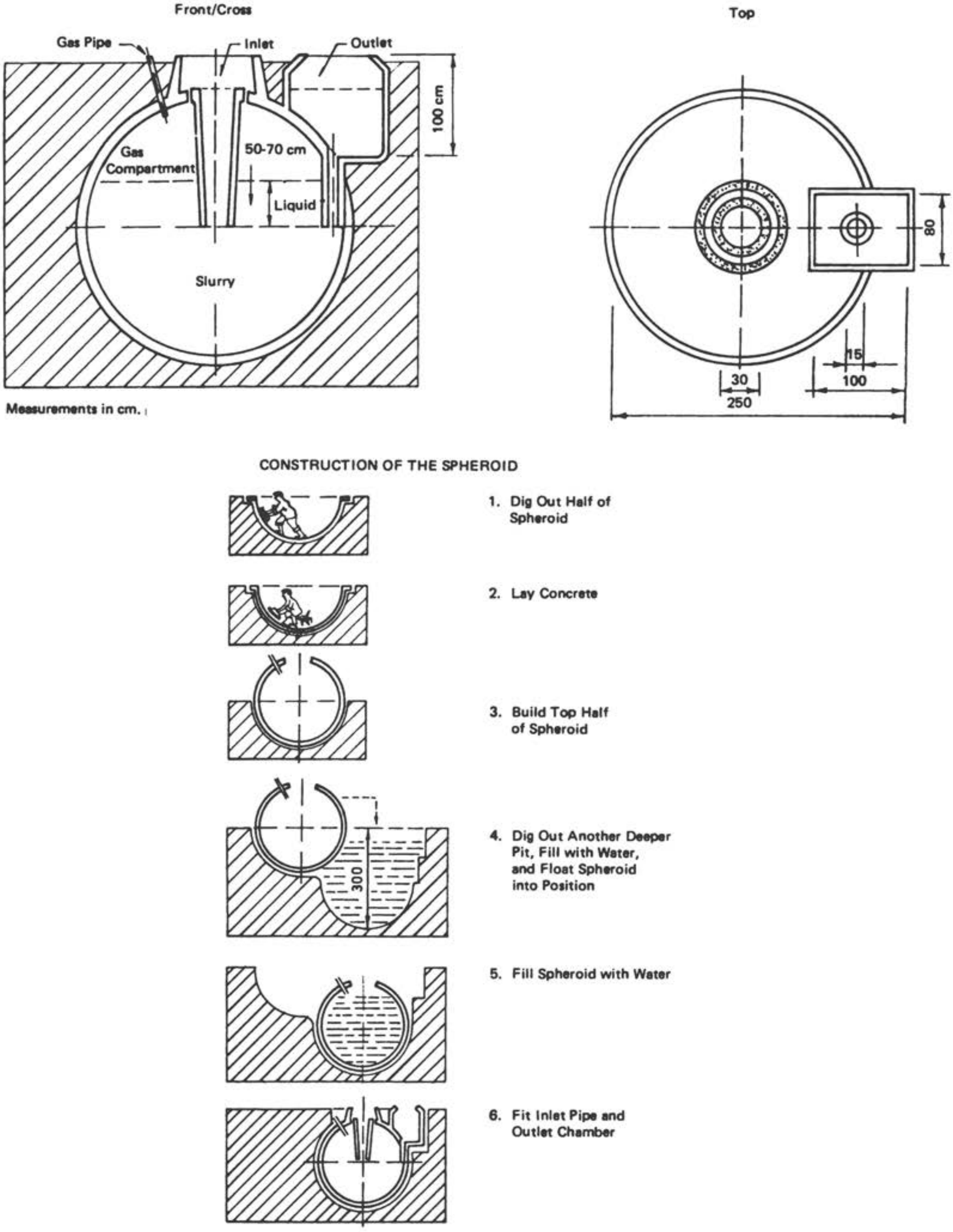


FIGURE 4.5 Design and construction of fixed-top ball digestor.

Agroindustrial Applications An anaerobic digestor for fruit and vegetable cannery wastes has been developed in Australia. At present, fruit and vegetable solid wastes are usually disposed of by dumping, burning, or feeding to animals. Since the wastes have a crude protein content of only about 4 percent, they have little value as feed. Also, although the wastes are offered to farmers free of charge for the hauling, transporting them beyond a few miles is uneconomical.

FIGURE 4.6 A biogas generator fabricated from reinforced plastic. The wood and metal racks can be weighted to increase gas pressure. (Lupton Engineering Corp.)

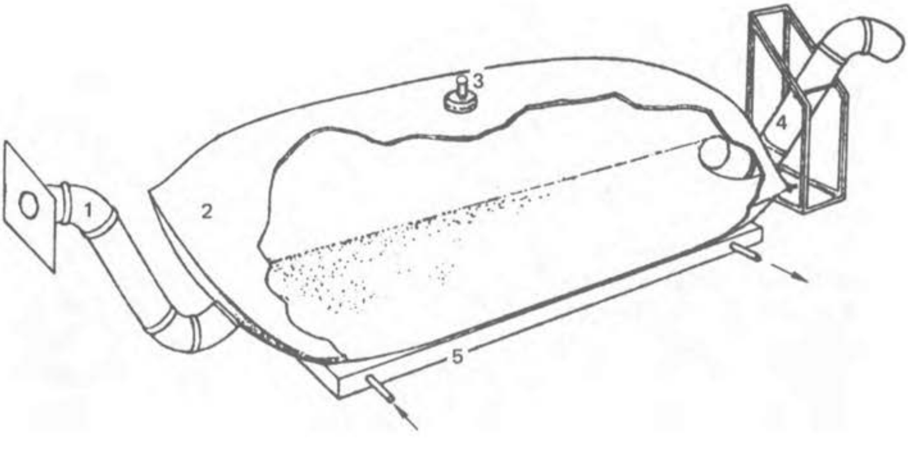


FIGURE 4.7 An above-ground bag-type biogas generator includes: (1) waste slurry inlet; (2) synthetic rubber tank; (3) gas outlet; (4) effluent pipe; and (5) heat exchanger. (Lockstoke Development)

FIGURE 4.8 Two 95-m^3 bag-type digestors used at the Animal Health Research Station near Bogor, Indonesia. The center column is used to scrub carbon dioxide and impurities from the biogas. The shed contains the controls, compressors, and heating systems for the digestors. (Sanamatic Tanks Pty. Ltd.)

A methane generator designed by the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) has been built that can handle up to 1 ton/day of wet fruit waste and supply part of the energy to run the cannery (Figure 4.11). If this unit proves successful, a digestor with a load capacity of 20 tons/day will be installed.

The Caribbean Industrial Research Institute, St. Augustine, Trinidad, is developing a system linking aerobic treatment with anaerobic methane generation. The aerobic process operates at 60°-70°C and effectively degrades wastes with a high lignocellulose content (bagasse, for example) in combination with animal manures. The partially degraded slurry from the aerobic treatment becomes the substrate for anaerobic biogas generation. Part of the heat generated in the aerobic reaction is used to maintain the biogas generator at 40°-42°C.

This dual treatment system has several potential advantages. First, the aerobic pretreatment of lignocellulosic wastes facilitates their conversion to biogas in the anaerobic unit. In addition, pathogens are unlikely to survive the high temperatures in the aerobic unit, so the final wastes can be used for fertilizer with less hazard. Using the heat from the aerobic step to operate the biogas generator at a higher temperature results in faster decomposition and higher rates of gas formation. However, the management of this system is likely to require more training than is needed for the use of simple anaerobic digestors.

For a viable biogas plant, a minimum of four or five confined pigs or cattle is needed. Although crop and human wastes can be used to reduce the need for manure, this restriction alone can eliminate many individual farmers; the investment required may reduce the number even more. An alternative is biogas generation at the community level. With this option, social problems of control and use arise. Successful community biogas units are operated by closed groups such as communes, kibbutzim, schools, experimental farms, and jails.

Municipally operated units for small towns and suburban clusters that combine the benefits of waste collection and treatment with biogas generation can also be considered in development strategy. For example, in a section of Baroda, India, a biogas plant using primarily human wastes supplied gas to several hundred households for several decades. The operation was abandoned only when the area was connected to the municipal sewage system. A similar plant is still in operation in the Dadar suburb of Bombay.

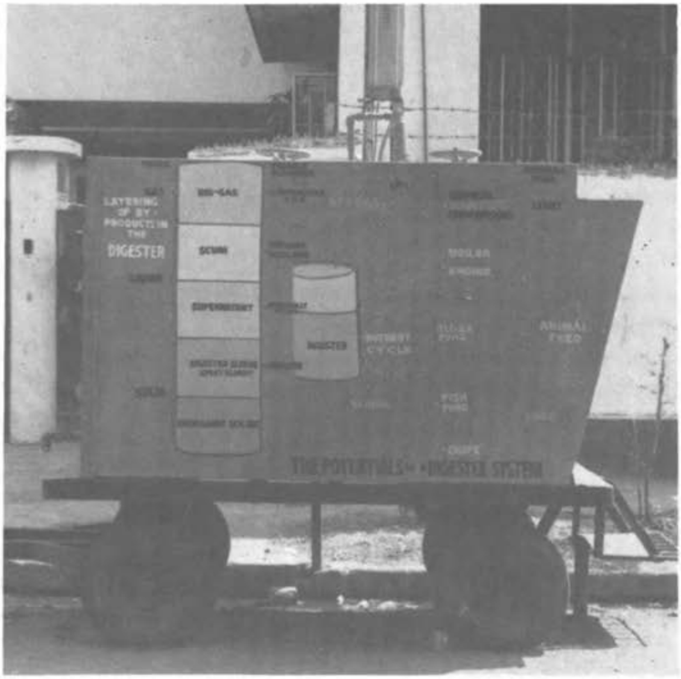


FIGURE 4.9 Philippine portable digestor. (Philippine Center for Appropriate Technology)

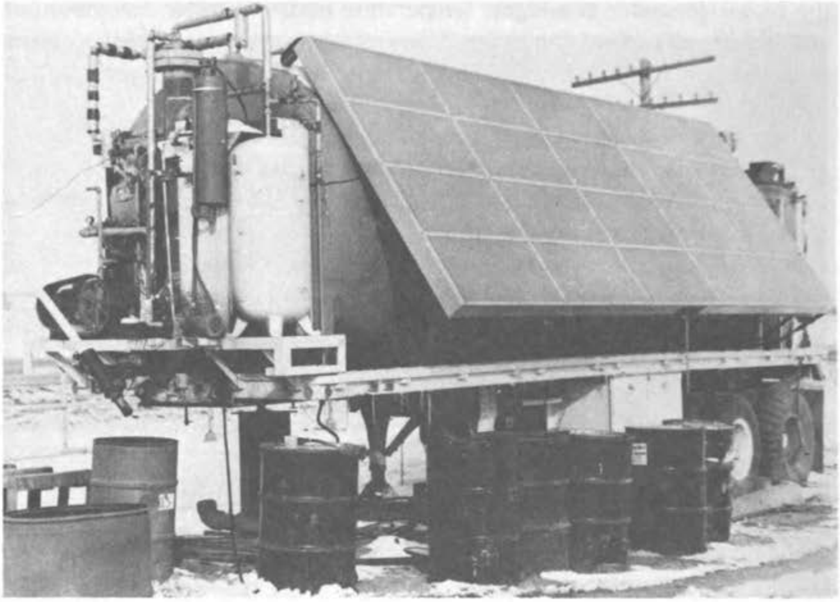


FIGURE 4.10 Used for on-farm demonstrations in the United States, this mobile biogas generator includes a solar panel to increase digestion temperature. (Biogas of Colorado)

In a recent cost-benefit study of an Indian community biogas plant in Fatehsing-Ka-Purwa, Bhatia and Niamir concluded that in this village the economic benefits did not exceed its costs. Some benefits, however, such as improved sanitation and fertilizer nitrogen recovery, were not quantified; some costs, including loss of personal flexibility in cooking and lighting hours, and the necessity of measuring and recording individual contributions and usage, were also excluded. Bhatia and Niamir also noted that the plan for this operation was conceived and executed entirely by state officials, without whose insistence it probably would not have been completed. It is also questionable whether the village is capable of maintaining the operation on its own. It is clear, therefore, that at any level–individual, village, or city–education, organization, and maintenance are needed for a successful operation.

Ethanol

If they are available in sufficient quantities and at a low enough cost, a number of cellulose-, starch-, and sugar-containing wastes can be converted to ethanol. All methods for the production of alcohol by fermentation involve the following steps:

- Collection and delivery of the raw material to an alcohol plant with storage facilities sufficient to compensate for irregularities in supply;

FIGURE 4.11 Australian methane generator using fruit wastes. (CSIRO)

- Pretreatment and conversion of the raw material to a substrate suitable for fermentation to alcohol, a process requiring little more than simple dilution for materials such as molasses and cooking for starchy materials to gelatinize the starch, which must then be hydrolyzed to sugars by acid or by enzymes;
- Fermentation of the substrate to alcohol and recovery and purification by distillation; and
- Treatment of the fermentation residues or the effluents to recover by-products for use as feed, fertilizer, or energy.

Of these steps, pretreatment and fermentation receive the most technical emphasis, but in practical terms, raw material availability is probably the most important. There is little value in building an alcohol plant unless it can be operated at near full capacity for most of the year. This means that the raw material should be continuously available, as the by-product or waste from an agroindustrial process might be, or that it should be capable of being stored without spontaneous degradation. Molasses and various grains meet these criteria, but many agricultural wastes or surpluses do not. For example, a vast quantity of coconut water, a waste material that contains about 2 percent of fermentable sugar, is produced. It is difficult, however, to collect and store this biologically labile waste. The heat required to concentrate it exceeds the calorific value of the alcohol that could be produced. Waste fruit and other spoiled produce may be excellent substrates for alcohol fermentation, but their availability is usually highly seasonal.

Treatment of large amounts of effluent from the fermentation plant raises additional problems, including possible environmental damage if untreated wastes are released to the waterways. A fermentation plant will produce about 10 volumes of stillage for each volume of alcohol. If the stillage–the residues remaining after the alcohol has been distilled off–has to be stabilized by evaporation, a considerable amount of heat must be supplied, even with the most efficient evaporators. On the other hand, stillage has been treated by anaerobic digestion to provide a small surplus of fuel in the form of methane.

In an attempt to convert whey to ethanol in Denmark, the waste from the distillation step was found to have unacceptable pollution characteristics. The costs connected with conventional treatment of this waste represented a serious threat to the overall feasibility of the project. When anaerobic treatment of this waste to generate methane was evaluated, it was found that the gas produced could replace about 20 percent of the fuel oil requirements of the distillation plant.

Initial processing of the raw material (for example, bagasse) may yield a residue that could be used to fire boilers, but it is of minimal value in any other application. The consumption of high-grade fuel, and particularly of liquid fuel, obviously should not be excessive, though some may have to be consumed in the collection and transport of the raw material.

Ethanol from Sugar-Containing Wastes There are several processes that produce sugar-containing wastes suitable for ethanol production. These include the preparation of cellulose pulp by the sulfite process, the manufacture of cheese, and the production of sugar. The nature and amounts of various sugars produced are listed in Table 4.1, as well as the approximate liters of ethanol that might be produced for each ton of primary product. Although coffee wastes (pulp and mucilage) contain fermentable sugars, an evaluation showed their conversion to alcohol to be uneconomic.

TABLE 4.1 Ethanol from Sugar-Containing Wastes

Primary Product	Waste Stream	Sugar Present	Approximate Kilograms[a] of Waste	Approximate Liters[a] of Ethanol from Waste
Cheese	Whey	Lactose (4.5–5%)	12,000	300
Paper pulp	Sulfite liquor	Hexoses, Pentoses (2%)	18,000	150
Sugar	Molasses	Sucrose, Glucose, Fructose (55%)	300	120

[a] Per ton of primary product.

Ethanol from Starch-Containing Wastes In Brazil, a starch-containing byproduct from processing babassu nuts has been converted to ethanol. Babassu nuts, which are harvested primarily for their oil, have a starch-containing layer that constitutes about 23 percent of their total weight. One ton of nuts can yield about 90 liters of ethanol from this starch as well as about 35 kg of oil.

Substandard bananas have been converted to alcohol as an intermediate step in the production of vinegar. In fact, in a survey of possible uses for food wastes and agricultural residues, Barnett and Fleischman suggest that the potential for the productive utilization of waste bananas is good because significant quantities are available year-round at central locations. In Ecuador they estimate that the yearly volume of waste bananas equals 68,000 tons of fermentable carbohydrate. Other major exporters of bananas, including Panama, the Philippines, and Costa Rica, also have large amounts of waste bananas.

Although wastewaters from the processing of starchy foods are potential substrates for fermentation to alcohol, their availability is usually seasonal and their starch content generally low.

Ethanol from Cellulose Wastes Cellulose is the prime useful component of most plant wastes. In India, for example, there are nearly 50 million tons of cellulose-containing agricultural by-products or wastes generated yearly, and cellulose constitutes about half of these wastes.

Of the cellulosic waste materials that are available in large quantities, the most important are rice and wheat straws, maize stover, rice hulls, bagasse, and paper mill wastes. Because of their lower proportions of lignin and higher levels of cellulose, agricultural residues and waste paper are more tractable substrates for ethanol production from cellulose than are paper mill wastes.

In the conversion of cellulose to ethanol, the cellulose must first be hydrolyzed to glucose by one of the following methods:

Enzymatic Hydrolysis: Cellulosic materials of different origin vary in their susceptibility to enzymatic hydrolysis. Even when the chemical composition of two cellulosic materials is approximately the same, their degradation by cellulose enzymes can be remarkably different. This reactivity is primarily related to the degree of crystallinity of the cellulose, with amorphous portions more readily degraded than more ordered sections.

Although chemical pretreatment methods such as alkali swelling have been used to enhance the reactivity of cellulose substrates, the products obtained are often too dilute (~5 percent) for further economic conversion.

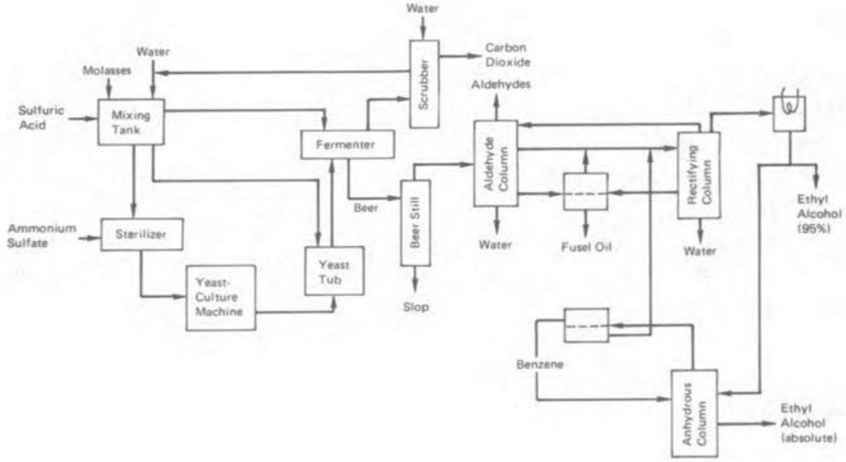
Ball milling has been found to be a successful pretreatment yielding a cellulose suspension in excess of 30 percent that can be hydrolyzed to obtain high concentrations of glucose. Ball milling, however, is an energy-intensive and costly process.

Acid Hydrolysis: Sulfuric and hydrochloric acids are commonly used for the decomposition of cellulose to fermentable sugars. Because the glucose formed in the reaction is susceptible to further reaction with these acids, the cellulose is heated to 200°-250°C prior to hydrolysis, and a short reaction time is used. The process must be balanced so that the rate of hydrolysis is high enough to compensate for the decomposition of the desired products. In addition, waste cellulose usually contains impurities that react with the acid to give undesirable by-products. Although acid hydrolysis processes can yield as much as 70 percent glucose, there are extensive handling and equipment problems associated with these procedures.

In spite of the great promise of using cellulose wastes for alcohol production, and extensive research in this area, there are as yet no commercially viable processes available for either enzymatic or acid hydrolysis.

Fermentation to Ethanol Whether the original waste contains starch or cellulose and requires conversion to sugars before fermentation, or whether it contains sugar to begin with, the final step in converting these materials to ethanol is essentially the same.

The fermentation process is typified in the production of ethanol from molasses (Figure 4.12). The molasses is diluted, acidified, and run into fermentation tanks, and a selected strain of yeast is added. The tanks are mixed and the fermentation proceeds for 2-3 days at 20°-40°C to produce an alcohol concentration of 8-10 percent. This mixture is distilled first to give 50-60 percent alcohol plus stillage. The alcohol stream is redistilled to give a 95-percent product. If needed, a final codistillation with benzene or another azeotropic agent can yield absolute (100 percent) ethanol. Recovery and practical use of the stillage (for example, as cattle feed) can profoundly affect the economics of the process.



Material and Utility Requirements

Basis—1,000 liters 95% ethyl alcohol
+ 4 liters fusel oil, 575 kg carbon dioxide, 120 kg carbon, and 108 kg potash

Molasses (blackstrap)	2,400 liters
Sulfuric acid (79%)	20 kg
Ammonium sulfate	1.8 kg
Steam	5,990 kg
Process water	10,000 liters
Cooling water	42,000 liters
Electricity	30 kWh (104 MJ)

FIGURE 4.12 Fermentation of molasses to ethanol.

Thermochemical Processes

For many agroindustrial operations, direct combustion of various residues is a matter of practical economics. Common examples include the burning of bagasse, cotton ginning waste, and rice hulls to provide processing heat.

Further, some work has been reported on the densification of wastes by drying, followed by mechanical compression to cubes or pellets. Through this process, residues such as straws or sawdust can be converted to dry, standard-sized fuels that are more easily stored, shipped, and used.

Apart from direct combustion, thermochemical processes for waste conversion may be considered in three general categories. The first is pyrolysis–simple heating of the waste to a high temperature in the absence of air. The second is gasification–controlled combustion of part of the waste to convert the remainder to a low-heating-value gas. The last is liquefaction, which is achieved by heating the waste under pressure in the presence of a reactive gas such as hydrogen or carbon monoxide. Each of these processes requires relatively dry cellulosic wastes.

Pyrolysis produces a mixture of solid, liquid, and gaseous fuels. The gas is often used to predry the waste or to dry crops, with the solid and liquid fuels retained for other domestic or agricultural use.

Gasification is usually aimed at producing a low-heating-value gas for on-site use, such as fuel for compression- or spark-ignition engines. This gas, commonly called wood gas or producer gas, has been successfully used to power both stationary equipment (pumps, electrical generators, furnaces, and kilns) and mobile equipment (tractors, buses, cars, and boats). It is the subject of a companion report.*

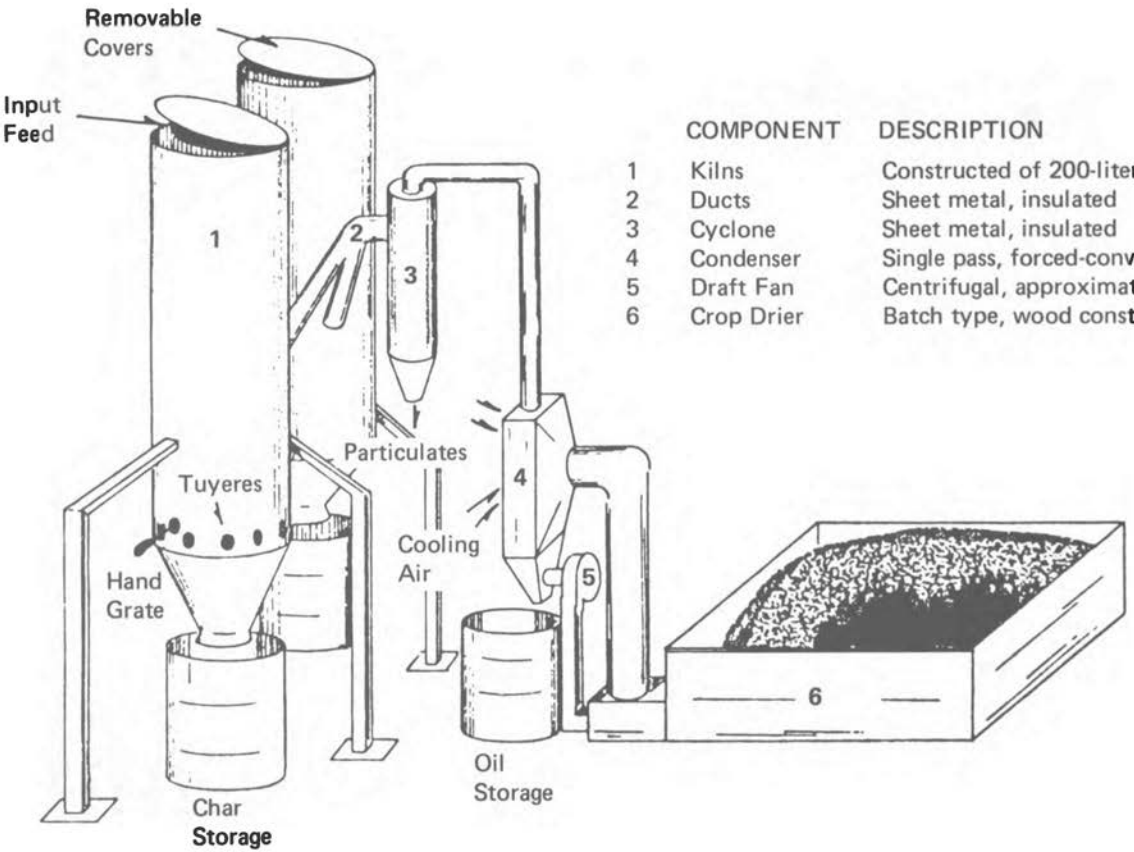
Liquefaction generally produces heavy oils as the primary product. In terms of current applicability, it is the most technically demanding and costly of these three thermochemical procedures.

Pyrolysis

A number of agricultural and forestry wastes have been tested in pyrolytic studies. In general, well over 80 percent of the heat value of the waste is retained in the gas, liquid, and char obtained, but in a more useful form. A simple batch-pyrolysis unit is illustrated in Figure 4.13.

Pyrolysis of agricultural wastes is far from new. Canadian work in the 1920s showed that 1 ton of sun-dried wheat straw, heated to 500°-600°C, could yield about 300 kg of char, 38 liters of a tarry oil, and 280 m^3 of gas (15,000 kj/m^3).

**Producer Gas: Another Fuel for Motor Transport*, National Academy Press, 1981.



	COMPONENT	DESCRIPTION
1	Kilns	Constructed of 200-liter oil drums
2	Ducts	Sheet metal, insulated
3	Cyclone	Sheet metal, insulated
4	Condenser	Single pass, forced-convection cooled
5	Draft Fan	Centrifugal, approximately 20 cfm
6	Crop Drier	Batch type, wood construction

FIGURE 4.13 A simple, 1-ton-per-day pyrolytic converter, which can be fabricated largely from available materials. Char and oil production plus crop drying can be accomplished through waste pyrolysis.

The results of laboratory pyrolysis experiments using dried cow manure, rice straw, and pine bark are shown in Table 4.2. With each of these wastes, the gases obtained contained significant amounts of carbon monoxide (18–40 percent) and hydrogen (14-38 percent). Although mixtures of CO and H_2 can be used for synthesis of methanol for fuel use, this is a capital-intensive, high-technology process.

TABLE 4.2 Pyrolysis of Agricultural Wastes

Waste	Reaction Temperature °C	M^3 of Gas[a]	kj/m^3	Liters of Oil[a]	kg of Char[a]	kj/kg of Char
Cow manure (3.6% moisture)	900	430	16,800	50	330	17,000
Rice straw	200-700	185	24,700	42	363	17,000
Pine bark	900	616	17,600	21	286	30,000

[a] Per ton of waste.
Source: Schlesinger, Sauer, and Wolfson, 1973.

In Indonesia at least 17 million tons of combustible wastes are produced each year. Rice hulls account for about a third of the total, and logging, sawmill, rubber, oil palm wastes, and bagasse the remainder. If pyrolyzed, an estimated 1.5 million tons of char and 0.9 million tons of pyrolytic oils could be produced. The energy content of these products would equal about 15 percent of Indonesia's total energy consumption.

An experimental pyrolysis unit has been built at the Institute of Technology, Bandung, Indonesia (Figure 4.14). In initial testing this unit converted about 65 kg of rice husks per hour to about 16 kg of char. A similar unit has been built at a nearby rice mill, since one of the objectives of this work is to use the pyrolysis gases to replace the diesel oil currently used to power the mill equipment.

At the Papua New Guinea University of Technology in Lae, pyrolysis of sawmill wastes is being tested in a 125-kg/hour pilot plant. A 25-50 tons/day pyrolysis system is planned for operation at a sawmill in Lae.

A small pyrolysis unit is being operated on sawdust and wood chips by the Technology Consultancy Centre, Kumasi, Ghana (Figure 4.15). The gas and oil produced will be used in a brick kiln and the char for cooking.

In the United States a pyrolysis unit currently being installed by the Tennessee Valley Authority has been designed to convert 3 tons/hour of wood into 150-190 liters of oil, 1 ton of char, and 7-8 million kj of gas. In addition, the Georgia Institute of Technology Engineering Experiment Station has developed a large-scale demonstration pyrolysis unit that can handle feed

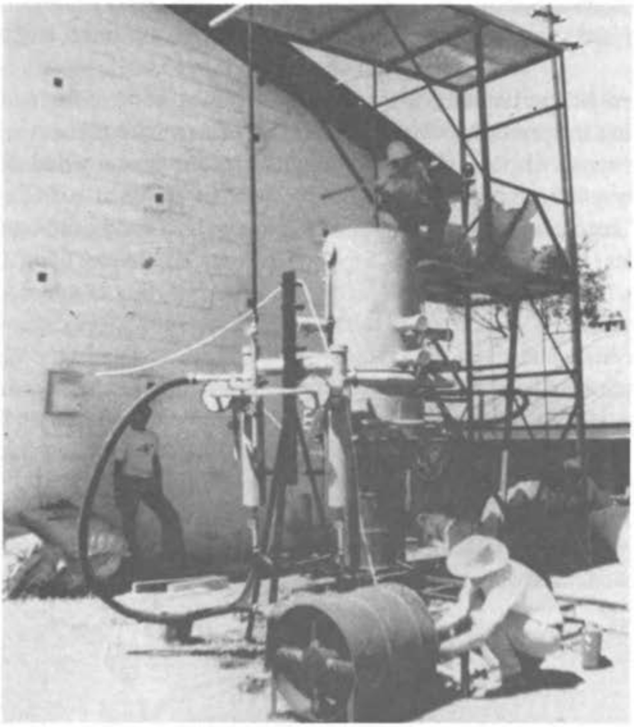


FIGURE 4.14 Rice hulls are converted to gas, char, and a tarry oil in this pyrolysis unit in Bandung, Indonesia. (J. Tatom)

rates of more than 50 tons/day. Wastes studied have included cotton gin trash, wood wastes, and peanut hulls.

Gasification

Gas generators have been designed and operated with almost every conceivable form of waste cellulose, including wood chips, sawdust, coconut husks, rice hulls, olive pits, straw, dung, walnut shells, and maize residues. Energy efficiency is about 85 percent–that is, of the energy contained in the solid waste, about 85 percent is recovered in the gas produced. From agricultural residues with an energy content of 14-21 mj/kg (6,000-9,000 Btu/lb), for example, a gas of 5,000-7,500 kj/m^3 (130-200 Btu/ft^3) is produced. For comparison, natural gas is about 37,500 kj/m^3 (1,000 Btu/ft^3).

An illustration of a typical downdraft gasifier is shown in Figure 4.16. Suitably dried wastes (about 20 percent moisture) are introduced at the top of the unit and are converted through a series of reactions to a combustible gas mixture. Ash is removed at the base of the gasifier, and tars, water, and particulate matter are removed from the gas stream before use in an engine (Figure 4.17).

Gasification can be particularly attractive as a power source for agro-industrial processing in situations where the waste is, of necessity, on site and may, in fact, represent a disposal problem. Examples include waste wood and sawdust at a lumber mill, rice hulls at a paddy mill, maize cobs at a shelling and drying plant, coconut husks and shells at a copra plant, and bagasse at a sugar mill.

Liquefaction

The U.S. Bureau of Mines has studied liquefaction of organic wastes for more than 10 years. Typically, manure reacts with carbon monoxide at 84 kg/cm^2 and 380°C for 20 minutes. About 570 liters of oil are obtained from 1 ton of dry manure.

In a process developed at the University of California, an aqueous slurry containing 25 percent wood is acidified and, at 80°C and 10 kg/cm^2, reacts to form an emulsion of wood sugars (hexoses and pentoses). This mixture

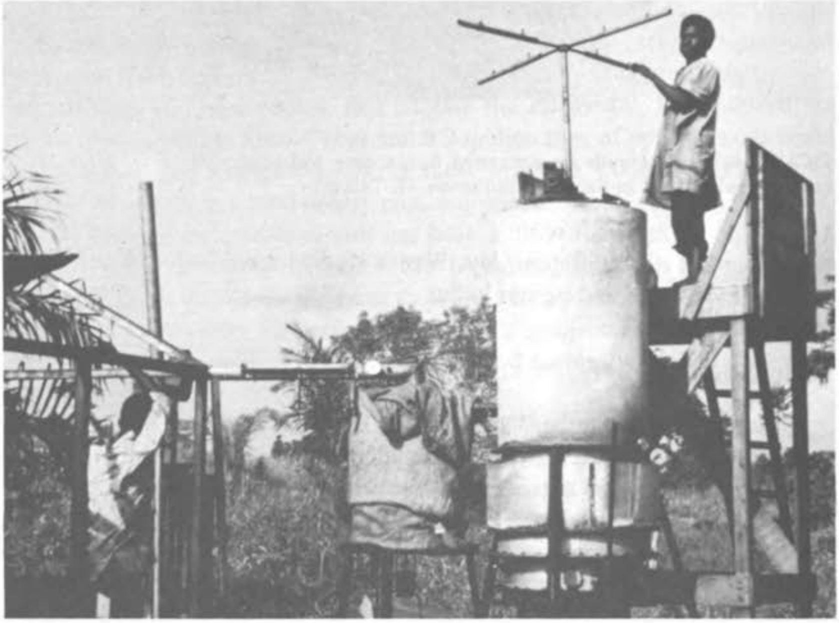


FIGURE 4.15 A pyrolysis unit in Ghana converts wood wastes to gas, oil, and char. Wastes are charged to the top of the tall center reactor. Char is obtained from the bottom of this reactor and oil from the condenser to its left. In this run, the gas is being flared from the stack at the far left. (Georgia Institute of Technology)

is then reacted with a 50-50 mixture of carbon monoxide and hydrogen at 370°C and 210 kg/cm². From 100 kg of wood, 30-35 kg of a 36,500 kj/kg oil are obtained (diesel oil is 45,600 kj/kg).

At the University of Toronto, researchers have hydrogenated a wood slurry at 340°C and 100 kg/cm². One kg of wood yields about 400 g of oil with a heating value of 35-38 mj/kg.

The evaluation of other wastes has shown that, although oil could be obtained from all the carbohydrate-type materials examined, the raw materials differed in ease of conversion to oil. The most resistant materials either had a high lignin content, as in Douglas fir bark, or consisted of high-molecular-weight crystalline cellulose, as in freshly cut wood. The most readily converted materials consisted of those forms of cellulose having some xylose units, corncobs, for instance. The xylose units are apparently weak links in the cellulose

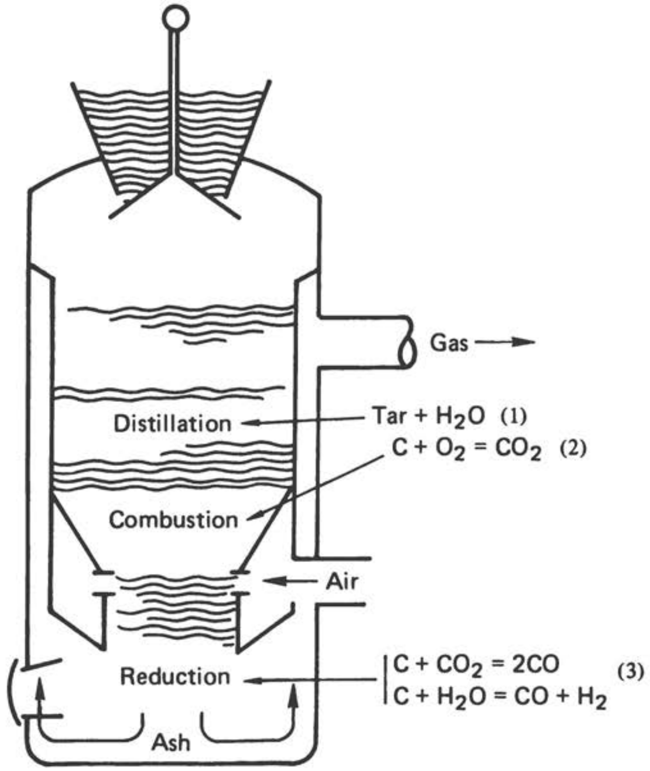


FIGURE 4.16 In a downdraft gasifier (1) tars and water are volatilized from the charge in the distillation zone to leave a char; (2) part of this char is burned to CO_2 in the combustion zone; and (3) part reacts with the CO_2 and water in the reduction zone to yield CO and H_2.

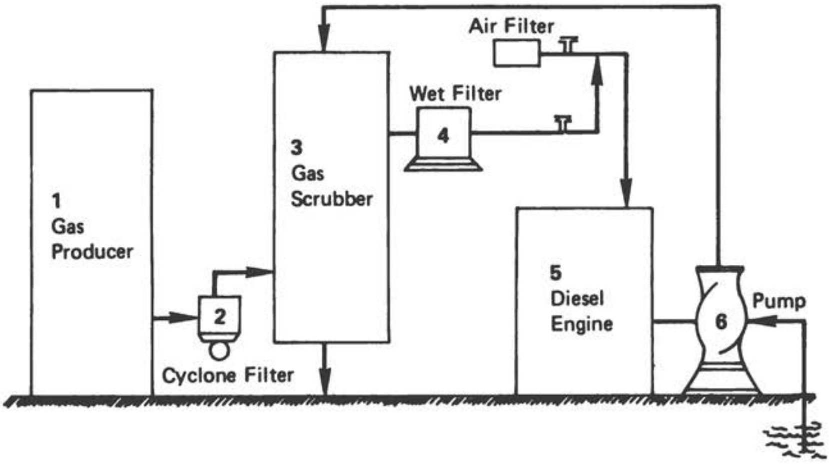


FIGURE 4.17 Exit gases from a gasifier are cooled and filtered before use in an engine.

polymer that facilitate breakdown to smaller, more reactive molecules.

Organic materials that have undergone considerable biodegradation are good raw materials for conversion to oil. Some fermentation residues have been converted to oil in good yields. Treated sewage sludge and aged manure have been used, but their high ash content can cause problems. In addition, although manures are desirable feedstocks for liquefaction in some respects (particularly their availability and homogeneity), their high nitrogen content limits the value of their oils. The nitrogenous compounds formed in liquefaction can cause sludge deposition in storage and can result in a higher nitrogen oxide content of the flue gas when the oil is burned.

Summary

Table 4.3 outlines the general potential for the various processes described in this chapter.

Limitations

For any of the waste-to-fuel processes, availability of capital is always a limitation. Where there is an environmental need for a waste disposal system, however, and where other fuels are costly or unavailable, one of the processes might be justifiable.

In order to operate higher technology processes, personnel would require extensive training.

TABLE 4.3 Potential for Biochemical and Thermochemical Wastes to Fuel Processes

Process	Scale[a]	Technology Level	Required Capital
Ethanol			
Sugar	V, C	Moderate	Intermediate
Starch	V, C	Moderate	Intermediate
Cellulose	C	In development	High
Biogas	F, V, C	Low	Low
Pyrolysis	V, C	Moderate	Intermediate
Gasification	V, C	Moderate	Intermediate
Liquefaction	C	In development	High

[a] V, village; C, commercial; F, farm.

Research Needs

For biogas systems, less costly and more durable centrally produced components could be an advantage. Also, systems capable of handling high flows of liquid wastes from agroindustrial processing plants are needed.

For alcohol production, more work is needed on simple systems to convert cellulose to sugar. Cellulose is the most abundant, lowest cost waste available in most parts of the world, and the economical conversion of cellulose to sugar, when it is developed, will have a profound impact on the type and amount of energy available from renewable sources.

For pyrolysis and gasification, demonstration units to evaluate various indigenous wastes would be valuable.

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5 Returning Wastes to the Land

The complex biological systems that serve to cycle organic wastes have developed over millions of years, principally in the soil. Until man established cities a few thousand years ago, almost all nutrient-laden organic matter was returned to the soil. Human activities have altered this cycle, and organic wastes have been diverted into waterways (Figure 5.1). However, since only a small portion of the human food supply is obtained from freshwater and marine life, it is more productive to return these nutrients to the land.

Plant production depends on a shallow layer of topsoil. Organic material enhances the retention and storage of water and improves the texture of this topsoil. A soft, friable soil allows penetration of air and water into the root zone and supports large populations of beneficial soil organisms.

Inorganic mineral nutrients are also utilized by plants. Mineralization of organic matter may occur through combustion, the basis for "slash and burn" agriculture, or through microbial transformation.

Crop production and erosion strip organic matter and mineral nutrients from the soil. Since the introduction of chemical fertilizers, many farmers have been able to ignore the importance of maintaining soil fertility by the restoration of organic materials. However, farmers in Asia, many of whom have limited access to chemical fertilizers, have not forgotten that it is vital to

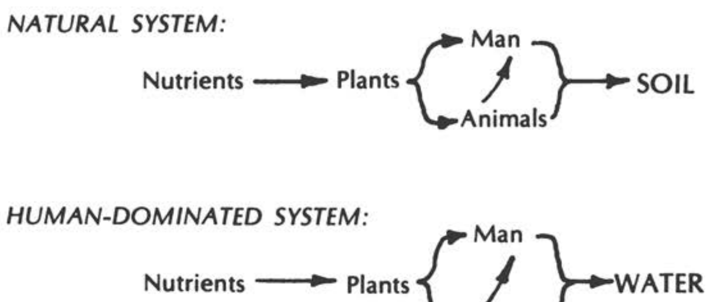

FIGURE 5.1 Human intervention results in wastes dumped in waterways rather than returned to the land.

husband their fields as their ancestors did for generations. In the People's Republic of China, about two-thirds of the total soil nutrients are reported to be derived from organic wastes.

This chapter includes information on methods of returning organic matter to the land to maintain soil productivity and to reduce dependence on chemical fertilizers. Although organic wastes are directly applied to the land without pretreatment in many countries, the presence of potentially dangerous organisms in human and agricultural wastes has led to the development of a variety of treatments that reduce this problem and yield products more beneficial to the soil. Treatments suitable for both solid and waterborne wastes are included.

Composting, as a means for treating solid wastes, is described. This aerobic biological process can convert agricultural and human wastes to humus for soil improvement. Larger organisms can also play a role in composting. Earthworms, for example, have been used for the treatment of sewage sludge and other wastes. When earthworms are used, the conversion process is called vermicomposting.

In the treatment of waterborne wastes both the nutrients and the water can be conserved. Untreated or partially treated sewage wastewaters have been utilized for irrigation of crops, pastures, and woodland. These wastewaters have also been treated by passage through lagoons in which water hyacinths are grown. In this case the water hyacinths are periodically harvested, composted, and applied to the land.

The use of wastewater for groundwater recharge and conversion to potable water is also discussed.

Solid Wastes

Composting

Composting is an aerobic biological process in which organic wastes are converted into humus by the activity of a complex of interacting soil organisms. These include microorganisms such as bacteria, fungi, and protozoa and may also involve invertebrates such as nematodes, potworms, earthworms, mites, and various other organisms (Figure 5.2). The relationships among the organisms account for the natural biocontrol and resulting balance of the population in the compost pile. A moderate number of creatures, therefore, are necessary in any functioning compost site, and no effort should be made to remove them with pesticides.

Nutrients are conserved through the process of composting. Some nutrients become adsorbed on the cellulose fibers of the waste, while others are incorporated within the humic pellets formed by the organisms. After compost

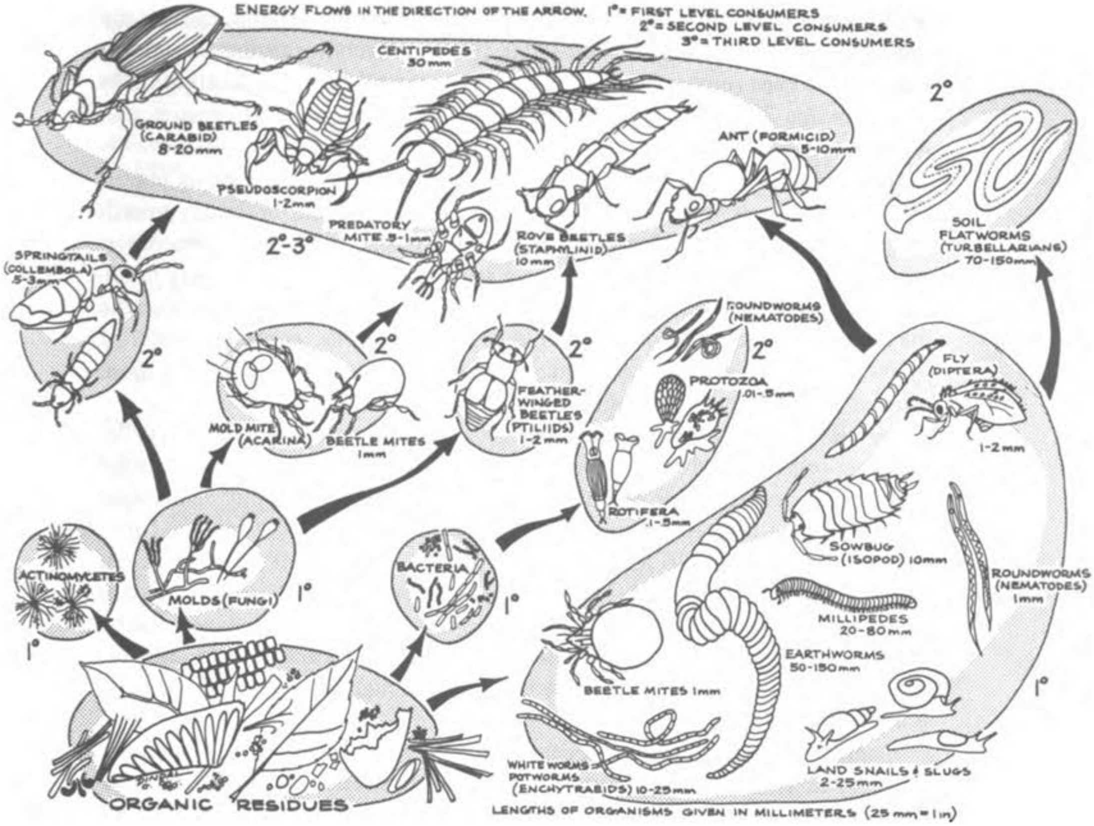

FIGURE 5.2 Food web of the compost pile. (D. Dindal)

is applied to the field, these nutrients are released slowly and made available to plants over long periods. Also, all of these organisms contain nutrients within their tissues which are held in abeyance during their lifetime and are not subject to loss by leaching. In essence, they are living sources of potential nutrients for the soil system.

Physical-Chemical Factors Factors affecting composting are those that influence most biological processes. These include moisture and aeration, pH, carbon:nitrogen (C:N) ratio, availability of phosphorus, potassium, and other mineral elements, and temperature.

Water content plays a particularly important role in composting. Organisms responsible for the decomposition in composting require conditions of high moisture but cannot withstand complete submergence. The proper water content of compost is about 50 to 70 percent—damp to the touch but not sodden. If all the air spaces in the pile become filled with water, nutrient leaching can occur, and undesirable anaerobic conditions develop, causing the important aerobic microflora and fauna to die or become dormant. Compost piles can be kept aerobic by physically turning the pile or incorporating stalks of plants like *Typha*, *Phragmites*, or bamboo, or pipes or tile to ensure adequate aeration.

The presence or absence of acids in the composting mass is another important factor. A pH range from 6 to 8 is desirable for the optimum growth of microorganisms, specifically bacteria and actinomycetes. Since decomposing waste matter contains many organic acids, the pH should be closely monitored. If compost becomes overgrown by molds, the pile is too acid and the decompositon rate will decrease. Lime, mollusc shells, egg shells, crushed bones, bone meal, or wood ashes mixed with the compost will provide a more efficient decay rate by neutralizing the acids.

As was noted in the discussion of biogas production, organisms that decompose organic residues require a certain amount of nitrogen relative to the available carbon for their growth. Although the optimal amount of nitrogen varies with the type of substrate and the organisms involved, typically 1 part nitrogen for every 15-30 parts of carbon present is needed. If this C:N ratio is lower than 15:1, nitrogen is lost by ammonification. The characteristic odor of ammonia is a sign that a carbon source such as shredded paper, leaves, sawdust, or other wood waste should be added; if the ratio is more than 30:1, decomposition will decrease considerably until a high-nitrogen-content waste is added (Table 5.1).

Composting will not occur in the absence of phosphorus and potassium. Phosphorus is a vital constituent in the energy transfer processes of microbial cells and potassium helps regulate osmotic pressure of the cells. If these elements are absent, chemical supplements can be used.

Inoculum or "Compost Starter" Microorganisms and invertebrates inhabiting compost will either be introduced naturally from the surrounding soil or from the waste items incorporated into the pile. A shovelful of rich soil will provide the inoculum best adapted for composting in a given geographic region. Studies have shown that commercial inocula are generally ineffective.

Effects of Heat Production Much heat is generated by microorganisms as organic waste decays. Early decomposition processes will be caused by mesophilic bacteria and fungi at 25°-35°C. Temperatures will rise to 45°-70°C when populations of thermophilic (heat-loving) bacteria, fungi, and actinomycetes increase and dominate decomposition. At these higher temperatures the population may be more than 10 billion microorganisms per gram of organic debris. The rate of temperature change from the ambient is increased by greater surface area of organic particles, ideal moisture content, and the proper C:N ratio.

TABLE 5.1 Nitrogen Content of Selected Waste Products

Material	N (%)[a]	C:N
Animal Wastes		
Urine	15–18	0.8
Blood	10–14	3
Fish scraps	6.5–10	5.1[b]
Mixed slaughterhouse wastes	7–10	2
Poultry manure	6.3	–
Sheep manure	3.8	–
Pig manure	3.8	–
Horse manure	2.3	25[b]
Cow manure	1.7	18[b]
Farmyard manure (average)	2.15	14
Night Soil	5.5–6.5	6–10
Plant Wastes		
Young grass clippings (hay)	4.0	12
Grass clippings (average mixed)	2.4	19
Purslane	4.5	8
Amaranthus	3.6	11
Cocksfoot	2.6	19
Lucerne	2.4–3.0	16–20
Seaweed	1.9	19
Cut straw	1.1	48
Flax waste	1.0	58
Wheat straw	0.3	128
Rotted sawdust	0.25	208
Raw sawdust	0.1	511
Household Wastes		
Raw garbage	2.2	25
Bread	2.1	–
Potato tops	1.5	25
Paper	0	–

[a] Total nitrogen.
[b] Nonlignin carbon.
Source: Methane Generation from Human, Animal, and Agricultural Wastes, National Academy of Sciences, 1977.

During this heating period, the hardy soil invertebrates will either become dormant or migrate away from the heated center of the mass to the periphery of the pile. The soil animals recolonize all areas of the pile once the heating subsides. Human and livestock pathogens and parasites, being less resistant to the world outside their hosts, are significantly reduced by the increased temperatures (Table 5.2).

If the compost pile is large enough, the heat generated may be used to heat living quarters (Figure 5.3) or water (Figure 5.4). By enclosing coils of water pipes within the composting mass, warm water may be obtained and pumped or convected from the pile into dwellings for household use. Several prototypes are being tested. In the United States one system, employing livestock manure and woodchip compost, is used during the harsh winters near

TABLE 5.2 Pathogen Survival in Composting and Agricultural Application of Human Wastes

	Survival in:	
Organism	Composting	Agricultural Application
Enteric viruses	Killed rapidly at 60°C	May survive up to 5 months on soil
Salmonellae	Killed in 20 hours at 60°C	On soil, *S. typhi* up to 3 months; other species up to 1 year
Shigellae	Killed in 1 hour at 55°C or in 10 days at 40°C	Up to 3 months
E. coli	Killed rapidly above 60°C	Several months
Cholera vibrio	Killed rapidly above 55°C	Not more than 1 week
Leptospires	Killed in 10 minutes at 50°C	Up to 15 days on soil
Hookworm ova	Killed in 5 minutes at 50°C and 1 hour at 45°C	Up to 20 weeks on soil
Ascaris ova	Killed in 2 hours at 55°C, 20 hours at 50°C and 200 hours at 45°C	Several years
Schistosome ova	Killed in 1 hour at 50°C	Up to 1 month, if damp

Source: *Health Aspects of Excreta and Sullage Management*, World Bank, 1980.

Syracuse, New York, while another, using rumen contents, is producing heat for farms in Nebraska. Compost piles can be used to heat vegetable patches to prolong the growing season in cool climates (Figure 5.5).

Compost Piles: Large and Small The simplest form of composting is illustrated in Figure 5.6. Layers of soil, manure, and plant residues are placed alternately in a crude bin. Depending on ambient temperatures and the composition of the wastes, the pile should heat up from bacterial action after a few days. With rewetting, as needed, and manual turning, the composting process should be completed in 4–12 weeks.

Another small-scale composting process used by Chinese farmers is illustrated in Figure 5.7. Animal or human wastes are mixed with crop wastes at a ratio of about 1:4, and elongated piles are prepared. Bamboo poles are inserted along the pile to serve as air vents, and the pile is enclosed with a plaster of mud. The poles are removed after 1 or 2 days when the mud has hardened. When the temperature in the pile rises to 60°–70°C after 4–5 days the holes are sealed. After about 2 weeks the pile is opened, turned, and resealed. Water is added, if required, at this point. Because of the temperatures achieved in this style of composting, pathogens are significantly reduced.

Large-scale composting on the community level can also be a successful endeavor; large-scale composting using forced aeration is shown in Figure 5.8. In this system, developed by the U.S. Department of Agriculture at Beltsville, Maryland, a mixture of wood chips and sewage sludge covered with sieved

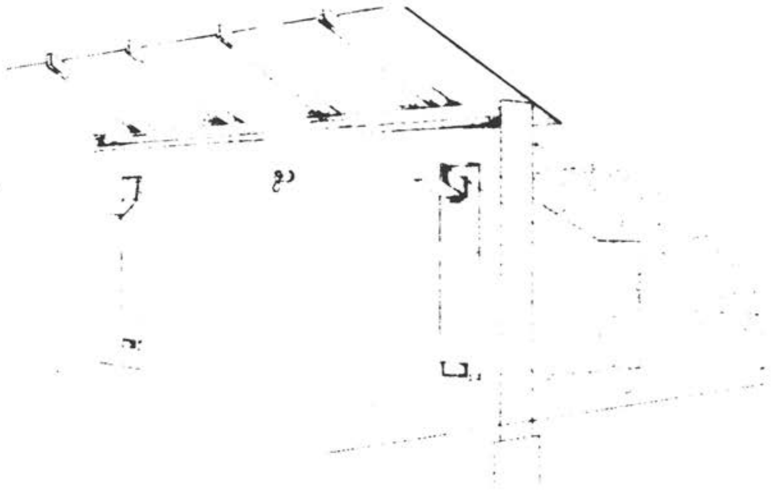

FIGURE 5.3 The heat generated in composting may be used for space heating . . .

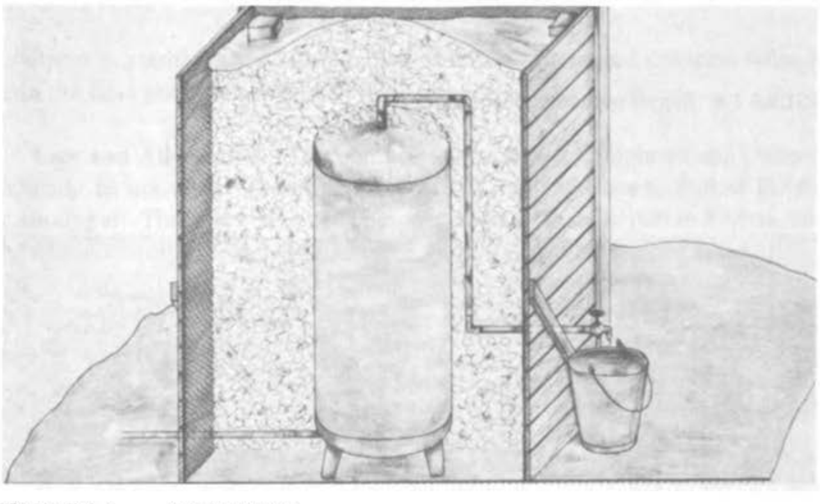

FIGURE 5.4 . . . heating water . . .

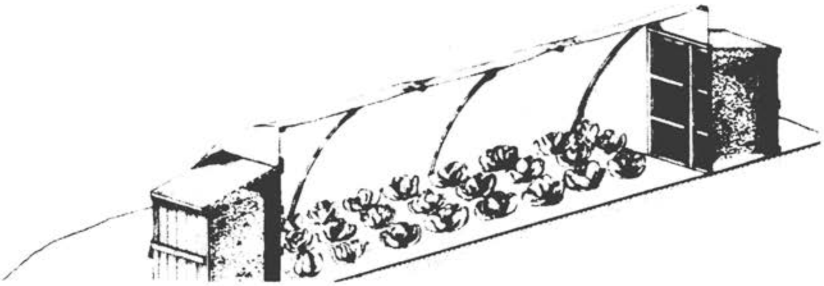

FIGURE 5.5 . . . or warming greenhouses.
Source: *Energy from Grape Marc,* G. Graefe, 1979.

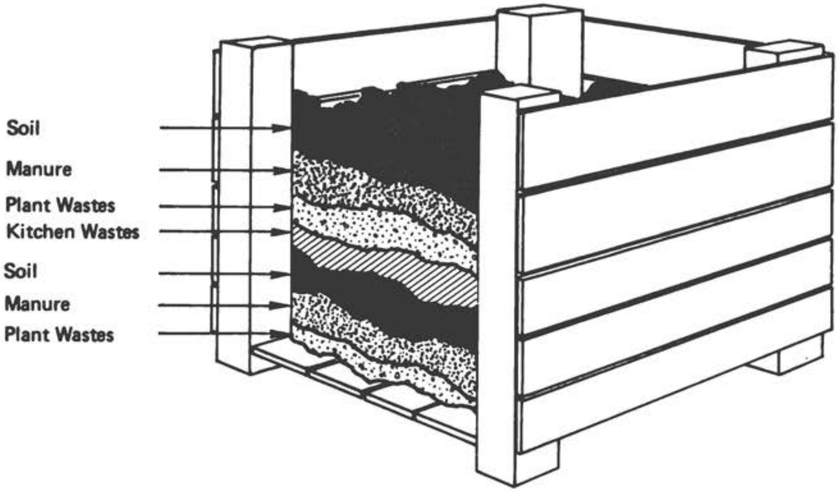

FIGURE 5.6 Simple outdoor composting.

FIGURE 5.7 One form of composting used in the People's Republic of China. A mixture of plant residues and manure is plastered with a coating of mud, and bamboo rods are used to form air passages. (FAO)

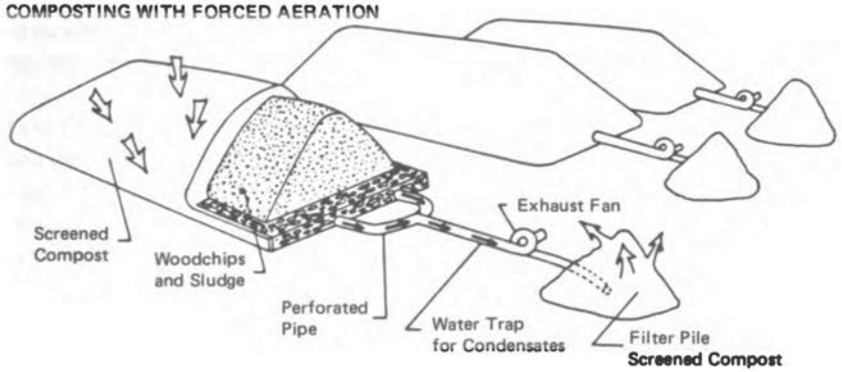

FIGURE 5.8 Diagram of the Beltsville Aerated Pile Method for composting sewage sludge. (USDA)

compost is continuously aerated. The covering of screened compost helps retain the heat generated without preventing the passage of air.

Uses and Alternatives The composting process is completed and compost is ready to use when the temperature within the pile drops to that of the surrounding air. The material in the compost pile will then be rich in humus, finely divided, crumbly, and dark in color, with a C:N ratio ranging from 10:1 to 20:1. Compost can be applied directly on top or worked into the soil or used for potted plants. It not only will provide nutrients but also will enhance the physical structure and water-holding capacity of the soil.

As composting systems become more complex, the labor and materials, and therefore costs, increase. An obvious alternate use for the same raw materials, crop wastes, and manures is in the generation of biogas. Simple composting systems are clearly less expensive than biogas generators. More elaborate composting systems may approach or exceed the cost of biogas systems. The comparison is important, because while both systems retain the fertilizer nutrient character of the waste, biogas generators also produce a useful fuel. Biogas reactor sludge may, of course, be composted, since the mesophilic biogas process may not kill or inactivate all pathogens.

Vermicomposting

The use of earthworms as a means of converting organic wastes to fertilizer and soil amendments has been termed "vermicomposting."

Under proper conditions, earthworms may consume almost any nontoxic organic waste including food processing wastes, paper, manures, and sewage sludge. Despite assimilation of some nitrogen during digestion, earthworm excreta (castings) may have a nitrogen content equal to the original content of the waste because of volume reduction. In addition, the physical character of the castings make them a superior soil-conditioning material.

The first commercial vermicomposting facility was established in Canada in 1970 and currently processes about 75 tons per week of biodegradable refuse. Similar facilities were established in Japan in 1974 and 1975 for processing special manufacturing wastes. And in the United States a demonstration process for converting residential refuse was started in 1975 in Ontario, California.

In Bangkok the Applied Scientific Research Corporation of Thailand is examining the use of redworms (*Eisenia foetida*) in processing digested sludge from the Siam Kraft Mill. Through burrowing and feeding, the worms effectively reduce the particle size of this paper waste. With this aeration and increased surface area the growth of aerobic organisms is enhanced (Figure 5.9). After the worms have been sieved out for transfer to a new batch of sludge, the material is suitable for use as a soil amendment.

Research on the use of redworms and nightcrawlers (*Lumbricus terrestris*) in the treatment of sewage sludge has been carried out in the United States at the College of Environmental Science and Forestry, Syracuse, New York. Studies have included the effects of earthworm feeding on different types of

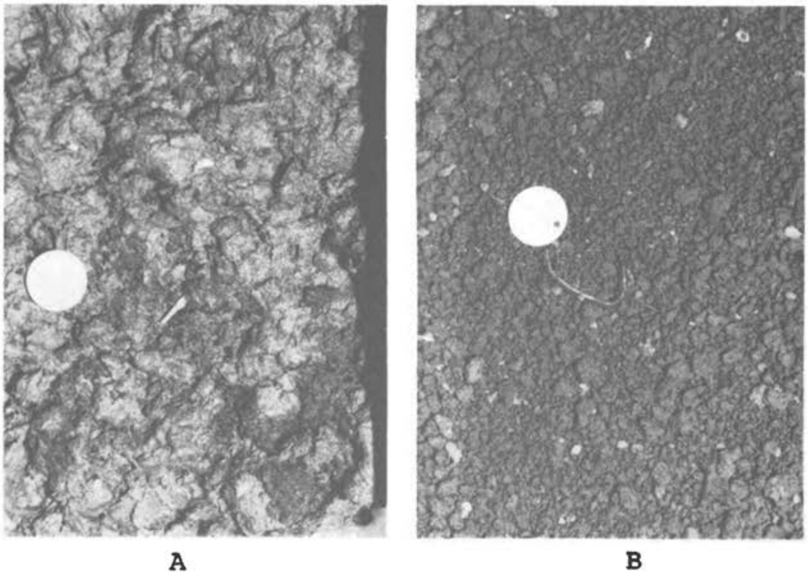

FIGURE 5.9 (A) Earthworms are used to convert digested paper sludge (B) to a more suitable form for land use. (N. Chomchalow)

sewage sludges (aerobic and anaerobic), the rate of throughput, and the character of the castings produced. Results indicate that anaerobically produced sludges are initially toxic to earthworms. When these sludges are placed on a mineral topsoil exposed to air, however, they are amenable to feeding by earthworms after 2 months. Aerobic sludges are readily consumed, with the decomposition rates increased 2-5 times by the presence of the redworm. Decomposition rates are accelerated because:

- Earthworm ingestion causes an increase in surface area of the sludge particles;
- Ingestion removes senescent bacterial colonies and stimulates new bacterial growth;
- Nitrogenous excretions from the worms enrich the soil formed from sludge;
- Earthworm burrowing enhances the oxygen penetration;
- Mineral nutrients are released through enhanced microbial mineralization; and
- Earthworm feeding increases the interaction among microflora, protozoa, and nematodes, improving the flow and exchange of nutrients.

The rate of sludge passage through the gut of worms is a function of moisture and temperature. Nightcrawler and redworm feeding is maximal at 15°C and 20°C respectively. A moisture content of about 85 percent appears to be optimal.

As *Eisenia foetida* feeds, the survival rate of *Salmonella enteritidis* (representing the pathogenic intestinal bacteria found in sludge) decreases by 29 percent per day compared with a 15 percent per day decrease in sludge without worms. Microflora within the earthworm gut are thought to outcompete the pathogen; it is also possible that the earthworms produce bacteriostatic substances.

The initiation and maintenance of mass cultures of earthworms are relatively easy processes, and the benefits are numerous. The earthworms' size permits ease of handling and production of large numbers in small areas (Figure 5.10). They are relatively clean creatures, generally harmless to humans, and therefore make good symbiotic partners in human activity.

In addition to the castings collected from earthworm cultures to enhance the structural friability, moisture-holding capacity, and aeration of soil, a large crop of earthworms can be harvested periodically to start additional cultures. They may also be used as a source of protein in feed for domestic animals (for example, poultry and fish). Dried worm tissues are also being investigated in Japan as a potential source of pharmaceutical compounds. For example, riboflavin is apparently produced and secreted by *Eisenia* sp.

FIGURE 5.10 Earthworms can be cultured in stacked trays for ease of handling and production in small areas. (N. Chomchalow)

Waterborne Wastes

Uses in Agriculture

The concept of applying wastewater directly to the land for the benefits of crop production through nutrient recycling is not new. The application of municipal wastes on farmland was practiced in Germany in the sixteenth century. The use of treated and untreated sewage effluent in various forms of farming continues today in Europe as well as Australia, India, Mexico, Argentina, and the United States.

Apart from the obvious advantage of conserving resources–valuable water supplies as well as the raw materials and energy used to produce equivalent quantities of fertilizer–land treatment can yield advantages in reducing the cost of construction, operation, and maintenance of treatment facilities. Unlike many complex wastewater treatment systems, land treatment relies on relatively simple primary or combination primary-secondary facilities, with the crop and soil systems serving as the "tertiary plant."

In a recent policy directive, the U.S. Environmental Protection Agency stated: "Land treatment is capable of achieving removal efficiencies comparable to the best available advanced treatment technologies while achieving additional benefits."

Virtually all essential plant nutrients are found in wastewater, including nitrogen, phosphorus, potassium, calcium, trace elements, and humus colloids. Studies in Poland indicated that wastewater irrigation transmitted 92 percent of its nitrogen, 86 percent of its phosphorus, and 71 percent of its potassium to the soil.

Using municipal wastewater for irrigation is especially attractive where agricultural lands are near cities. Some treatment of sewage should precede land application, but for many crops the degree of treatment is so low that little technology and capital investment are required. Mexico, for example, uses vast amounts of untreated sewage as irrigation water.

Since 1892 Melbourne, Australia, with a present population of almost 2 million, has used treated sewage as irrigation water at the 109-km^2 Board of Works farm at Weribee. The farm grazes 15,000 cattle a year, and 40,000-50,000 sheep are fattened during the spring and summer. Health restrictions are imposed on the sale of cattle and sheep for slaughter, but the 0.02 percent condemnation rate for carcasses is the same as that for the surrounding area. No higher incidence of disease among farm employees has been found to result from their occupation.

In Libya, spray irrigation equipment is being installed that will utilize municipal wastewater from the city of Tripoli. About 750 hectares of land, under the control of the Hadba El Kadra Extension Project Authority, will be irrigated to produce forage for livestock feed.

Sopper and Kerr, at the Pennsylvania State University (United States), have observed numerous positive responses from the spray irrigation of municipal wastewater in forests, old fields, pastures, and cropland. Water is relieved of its nutrients and colloidal organic load as it passes through the organic litter and the upper 15 cm of soil. This zone, rich in soil organisms, has been called a "living filter."

As a result of this irrigation, earthworm populations were significantly increased on the sites. They added to the positive effects of the living filter by increasing the potential for organic matter incorporation and recycling of the nutrients within the soil system. In addition, the increased earthworm populations caused increased soil porosity and water-holding capacity.

The impact of the living filter was also shown by crop yields from fields irrigated with wastewater as compared with those sprayed with ordinary water. Hay yields increased as much as 300 percent and maize 50 percent. Other increased yields associated with various application rates are shown in Table 5.3.

Sopper has also observed dramatic results using wastewater for the irrigation of a hybrid poplar fuelwood plantation. In a 5-year study, wastewater-irrigated plots yielded more than double the woody biomass of the control plots, suggesting the potential for yields of 29-35 dry tons per hectare. The plantations were also very efficient in renovating the wastewater entering the groundwater reservoir.

TABLE 5.3 Crop Yields at Various Levels of Wastewater Application

		Irrigation Level in Inches per Week		
Crop	Unit	Zero	1	2
Alfalfa	tons/acre	1.95–2.27	3.73–4.67	4.38–5.42
Maize (grain)	bushels/acre	63–81	103–121	105–116
Maize (silage)	tons/acre	3.11	3.93	4.32
Oats	bushels/acre	45–82	80–124	73–97
Red clover	tons/acre	1.76–2.48	4.90–5.30	4.59–5.12

Source: Sopper, W. E. and L. T. Kardos, 1973.

Vermes and Szlavik have reported on the results of land application of various wastewaters in Hungary. Effluents from fruit and vegetable canneries, breweries, sugar beet mills, dairies, distilleries, and potato-maize starch factories have all been used successfully on field crops.

Cannery wastes from a factory in southern Hungary are mechanically treated to remove larger particles and oils and then used for surface irrigation of a 97-hectare poplar plantation. Brewery wastewaters (about 1,300,000 m^3/year) are used to irrigate alfalfa, maize, wheat, and poplars on a 483-hectare treatment farm.

Waste Stabilization Ponds

Waste stabilization ponds (oxidation ponds) have been recognized as effective and economical units for treatment of domestic sewage as well as biodegradable industrial wastes. This biological process involves the symbiotic activity of algae and bacteria in the presence of sunlight, atmospheric oxygen, and nutrients in the wastewater. The low cost of these ponds makes it possible to bring sewage treatment within the reach of smaller communities and help reduce environmental pollution. In stabilization ponds the wastewater nutrients are removed from solution and concentrated in the algal cells. Since the effluent from the pond carries with it a considerable quantity of algae, the harvesting of algae from the pond effluent is a means of recovering nutrients from the wastewater. The production of algae from wastewaters for use as animal feed is covered in Chapter 3.

Wastewater Renovation Using Water Hyacinths

The water hyacinth *Eichhornia crassipes*, a large floating tropical plant, can be used for the removal of impurities from water. Experiments have shown that the plant will absorb nutrients, metals, and trace organic substances from water.

A German botanist, Carl Friedrich Philippe von Martius, discovered these hyacinths in the Amazon Basin in the early 1800s. These benign-appearing plants with their beautiful bluish-purple flowers were transported to other warm regions of the world where they now flourish. The prodigious productivity of the water hyacinth has given it an almost legendary status. It is likely that the hyacinth is the most productive macrophyte on this planet. This productive capability, it should be noted, occurred without selection or genetic manipulation by man. In fact, man has waged incessant warfare on this species since it began to invade habitats such as man-made canal systems. Hyacinth reproduction is essentially vegetative. A "mother" plant extends stolons, forming "daughter" plantlets. Daughter plants, in turn, produce offspring. A "family" of plants may remain connected for some time by stolons in still waters. Mat formation continues until the water surface is covered, and numerous roots suspended into the water become the dynamic filtering surfaces.

Hyacinth culture can be employed in conjunction with stabilization ponds. Controlled hyacinth culture in stabilization pond effluent produces an effluent of high quality. A properly designed and operated hyacinth culture unit will significantly reduce fecal coliform levels and yield an effluent with low suspended solids and biochemical oxygen demand.

The use of water hyacinths for wastewater treatment is a rapidly expanding technology. It offers the promise of a relatively simple means of treating wastewater while producing plant biomass that can be coverted to feed, fertilizer, and energy. This low-energy process also has the potential for small-scale as well as larger-scale applications. During the past 7 years, Wolverton, at the U.S. National Space Technology Laboratories (NSTL) in Mississippi, has conducted research in the use of these plants for waste recycling. A "Water Hyacinth Wastewater Treatment Design Manual"* has been developed from research by NSTL and other U.S. researchers.

The following design considerations are used by the Texas Health Department for hyacinth culture basins:

- Basin Sizing—Hyacinth basins should be sized for a maximum surface loading rate of 1,900 m^3/ha/day with a mean water depth of 1 m. A maximum basin size of 0.4 ha is recommended.
- Basin Configuration—Rectangular basins having a length-to-width ratio of at least 3:1 would be preferable. Basins should be designed to approach plug-flow conditions. Influent should be introduced at intervals along the upper margin of the basin. Increased efficiency may

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*Available from National Technology Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161, USA.

be attained by dividing a rectangular basin into equal parts by a diagonal, low earthen dike. Influent distributed along the base of one right triangle would be collected at the apex, and reintroduced along the base of the other triangle.

- Dual Systems—Duplicate systems, each having a capacity to treat the average daily flow of the facility, must be provided. Constant inflow should be maintained to the culture basins. The feeder stabilization pond should serve for flow equalization, with the water level in the feeder pond rather than in the culture basin allowed to fluctuate. Only surface water from the stabilization pond should enter the hyacinth culture basin.
- Barrier—A fixed barrier creating a clear zone of approximately 1 percent of the basin surface area must be installed around the outlet to retain the hyacinth plants, allow for reaeration, and prevent the discharge of plant debris.

System hydraulics are an important consideration in hyacinth culture unit design. In designing a culture unit it should be assumed that the water-flow path through a basin will be directly from the influent to the effluent. Figure 5.11 is a suggested configuration for a culture basin.

Harvested hyacinth can be composted (Figure 5.12) or used to produce biogas. Land application of the compost or of the digestor sludge effectively recycles the wastewater nutrients.*

Groundwater Recharge

Water removed from underground aquifers is usually replaced by natural recharge, but extensive well systems may withdraw more water than is replaced. In these cases, surface water can be used to replenish the water table, a process known as artificial recharge. In some areas, wells are drilled or pits are dug to give surface water entry to the aquifer; elsewhere water is spread on the land, and unaided, it percolates through the soil to the aquifer. This last method is appropriate for aquifers near the surface. Pits or wells are used where aquifers are deeper. These methods are inexpensive, require minimum technical expertise for operation, and are effective in areas with appropriate geohydrology.

There is growing interest in artificial recharging of groundwater because it provides ready-made storage reservoirs, free from evaporation and protected against pollution. Replenishing groundwater sources also may keep neighboring saline waters from intruding into the aquifer or soil from collapsing into a depleted aquifer. An interesting application of an indirect recharge is practiced in Amsterdam, Holland, where the municipal water department pumps water

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******Making Aquatic Weeds Useful: Some Perspectives for Developing Countries*, National Academy of Sciences, 1976.**

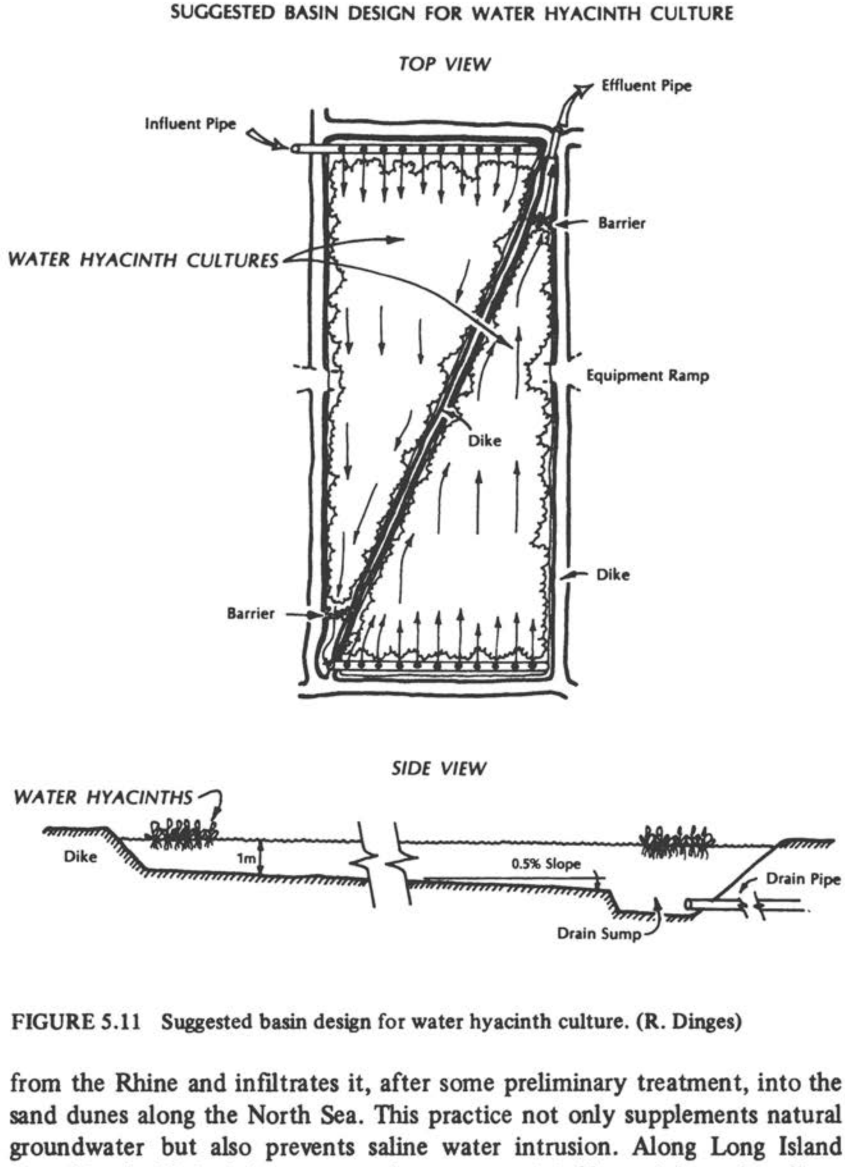

FIGURE 5.11 Suggested basin design for water hyacinth culture. (R. Dinges)

from the Rhine and infiltrates it, after some preliminary treatment, into the sand dunes along the North Sea. This practice not only supplements natural groundwater but also prevents saline water intrusion. Along Long Island Sound in the United States, treated wastewater is infiltrated through wells to form a barrier against seawater infiltration to protect the freshwater aquifer. The feasibility of direct infiltration of treated sewage depends on aquifer characteristics. Some aquifers may require so much pretreatment that direct reuse becomes more attractive.

Sewage farming is an indirect form of groundwater recharge. Both raw and treated sewage is used and undergoes treatment in the soil. If such groundwater is used for human consumption, however, quality should be carefully monitored and treatment processes provided to safeguard human health.

FIGURE 5.12 Completed compost heaps from water hyacinth, Barisal Irrigation Project, Barisal, Bangladesh.

Reuse as Potable Water

Potable use places the highest demands on water quality. Wastewater must undergo extensive treatment to make it suitable for drinking. Processes for removing ammonia, nitrates, and phosphates are available. Residual, potentially toxic organic compounds can be reduced to very low levels by adsorption on activated carbon. Dissolved mineral matter can be reduced to acceptable levels by ion exchange, electrodialysis, or reverse osmosis. These processes, however, can double or triple the capital and operating costs of a conventional treatment plant.

Producing water of acceptable quality requires a large investment in capital equipment and high recurrent costs for power and chemicals. Although the cost of such water is relatively high, it may be lower than that of desalinated seawater. In arid lands it may be lower than the cost of developing alternative supplies of water. For example, Windhoek, Namibia, a city of 84,000, meets one third of its water needs by treating and recycling 4 million liters/day of sewage into the potable water supply.

Integrated Reuse

As an example of integrated reuse of wastewater and solid wastes, in India the National Environmental Engineering Research Institute, Nagpur, and College of Engineering, Madras, have used stabilized pond effluent for fish polyculture. The effluent is then used in the cultivation of coconut palms, fodder grass, and other long- and short-duration crops (Figure 5.13).

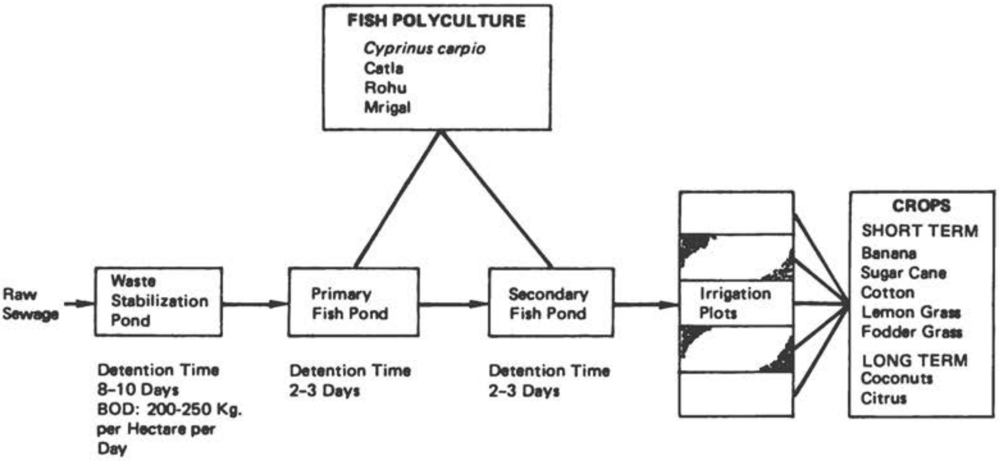

FIGURE 5.13 Layout for an integrated wastewater treatment and utilization system. *Source*: National Environmental Research Institute, Nagpur, India.

Limitations

In any process where pathogen-containing wastes are used directly or indirectly for the production of food or feed, the potential for disease transmittal exists. Also, for processes that extract or concentrate nutrients from waste streams, the potential for heavy metal or toxic organic compounds accumulation exists.

Although the waste conversion processes described require relatively low levels of technology, determination of residual pathogens or toxicants requires high technological capability. This requirement should be considered before these processes are implemented.

Research Needs

Research is needed on ways to reduce costs and minimize potential health problems. In addition, for wastewater use in agriculture, data is needed on the effects of long-term application where trace levels of some elements may cause irreversible damage.

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6 Integrated Systems

Each of the preceding chapters has centered on a particular facet of waste usage—in aquaculture, for example, or in the conversion to fuel, food, feed, or fertilizer. Although each of these processes can have individual merit, the optimum in waste use would be an essentially closed, self-sustaining farm unit with few inputs apart from sun and water.

The purpose of this section is to indicate how various technologies might be integrated to meet specific goals. The examples cited are intended to be merely illustrative. Potential users should design systems that fit their needs, resources, and technical and managerial skills.

Some of the systems described are under study in research institutions and in demonstration projects, while others are in field development and use.

In all cases, however, the objectives and advantages include:

- Increased resource utilization;
- Maximized yields;
- Expanded harvest time based on diversified products;
- Marketable surplus; and
- Enhanced self-sufficiency.

Basic to any integrated system and common to many land holdings would be a social unit (home, village, community) supported by crops and livestock. Figure 6.1 illustrates some of the simpler possible systems that could be based on these three elements to maximize the conservation of nutrients and other resources, protect public health and environment, and achieve desired social goals.

Central to the top portion of Figure 6.1 is a composting unit, which would be used to accumulate all the wastes from the home, garden, and livestock and convert them to fertilizer.

With the same waste inputs, it is possible to substitute either a biogas generator or a fish pond for composting. For example, if the composting unit in this diagram were replaced by a biogas generator, the same wastes would provide both fuel and fertilizer. In turn, if the composting section were replaced by a fish pond, both food and fertilizer could be obtained.

Comparing these three systems in terms of external inputs (materials and

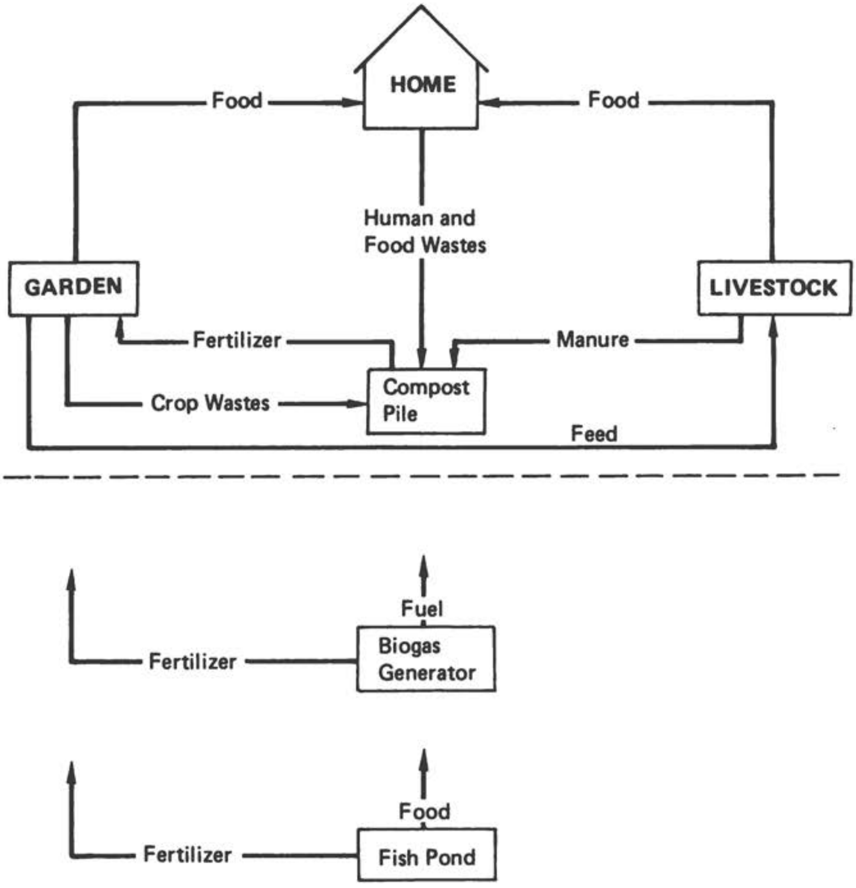

FIGURE 6.1 Possible integrated systems. With the same general type of waste inputs, a biogas generator might be substituted for the compost pile to yield fuel in addition to fertilizer, or a fish pond substituted to yield food in addition to fertilizer.

training), the composting system would be least demanding. The operation of a fish pond would require excavation, fish purchase, and training in fish production. The training for operating a biogas unit would probably be equivalent to that required for the fish pond, but the total investment in construction and purchased components would probably be greater.

Significantly more complex integrated systems that include biogas generators, fish ponds, and other elements have been proposed or tested by various researchers, and integrated systems that combine several aspects of waste reuse have been described, representing small- and large-scale operations.

Small-Scale Integrated Systems

In Vanimo (Papua New Guinea), Frankel developed a system for a health center that included a biogas generator, an algae pond, a pond for fish and ducks, and an irrigated garden (Figure 6.2). Tilapia yields of up to one ton/year were estimated and about 200 ducks per year were reared. Garden crops flourished. The returns from this unconventional waste system on a moderate capital outlay (less than $1,000) were impressive, particularly since a conventional system would have cost almost as much.

In Thailand an integrated farming system is being tested as a model for future development (Figure 6.3). This small farm covers about 0.4 hectares with two main sections–a 1.25-m-deep fish pond and a vegetable garden–each of about 0.2 hectares. A flat-surfaced dyke divides the two sections and continues around the plot to retain the water and reduce external flooding.

A simple two-level wooden structure is constructed on the central dyke to house both the family and livestock. The ground floor extends over both the pond and garden areas. Pens for up to 30 pigs are constructed in these overhanging areas. Just above these pens on the outer edges of the building are two rows of wooden enclosures for up to 60 laying hens. The top floor

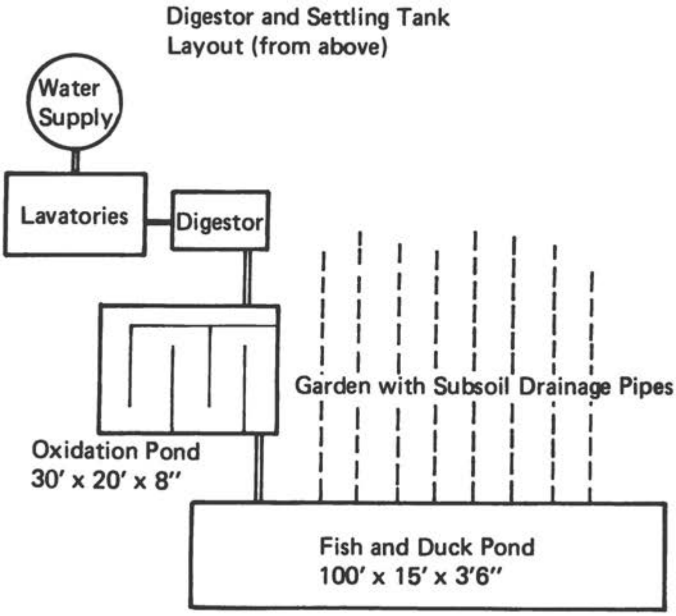

FIGURE 6.2 An operating integrated system in Papua New Guinea.
Source: Frankel, 1977

FIGURE 6.3 An integrated farm system in Thailand. (M. Sundhagul)

provides accommodations for a family of four. The roof of the building has gutters to collect rainwater for drinking and cooking.

Chicken wastes provide supplemental pig feed. Part of the pig wastes acts as fertilizer for the fish pond, and part is used on the garden. About 5,000 fish (tilapia) can be reared in the pond, and maize, beans, and other vegetables can be grown in the garden. Periodically, the garden and pond areas are interchanged to utilize the high-nutrient pond sludge as plant fertilizer and to help control plant and fish diseases.

In a cooler climate (Cape Cod, Massachusetts) the New Alchemy Institute (NAI) has studied and practiced a wide variety of waste reuse systems. In one of these (Figure 6.4), a greenhouse using sun and wind energy is used to supply fish and vegetables. In a system of three ponds at successively lower levels, wind power is used to pump water from the lowest level through a solar water heater to the highest level. In the first pond, the water is purified by trickling through a bed of clam shells, rock, and earth. In the second pond, daphnids, cyclopids, and algae are cultured. This pond overflows into the last and largest pond sweeping along these organisms to the tilapia. The water in these ponds helps provide a heat reservoir for the plants growing in the en-

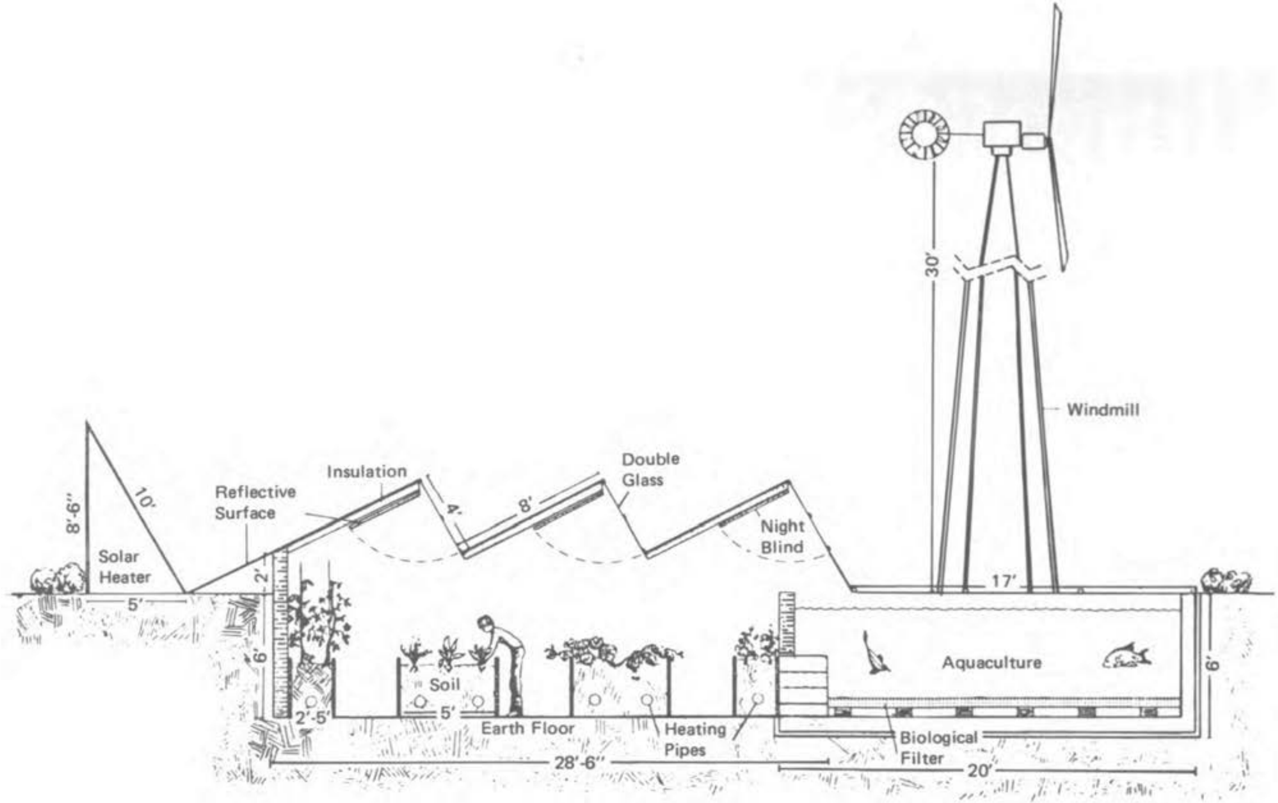

FIGURE 6.4 A solar-heated greenhouse-aquaculture complex for cooler climates. (NAI)

closure and these plants are used in part as fish feed, in part as food. Some of the nutrient-rich water is also used to fertilize gardens outside the enclosure. The NAI is also working with composting, earthworm culture for fish food and waste disposal, and home solar heating.

The ancient Mexican "chinampa" system of self-sufficient agriculture has been proposed for wider use by Gomez-Pompa. Small plots of land separated by water channels are used. These so-called floating gardens are artificial islands built in shallow water by piling up layers of aquatic plants and silt from the bottom of lakes. In order to keep the porous soil of the chinampa perpetually moist by infiltration of the surrounding waters and to facilitate manual irrigation, the islands are built in narrow strips. Since the water level changes in some of the lakes used for chinampas, the soil surface is adjusted—by adding or scraping—in relation to the water level to assure that moisture reaches the root zone. Additional moisture is supplied directly to the individual plants by lifting water from the surrounding canals (Figure 6.5).

Chinampa nutrients are derived partly from nitrogen-fixing plants such as *Azolla* and partly from human and animal wastes. Seeds are started in specially enriched beds prepared from channel mud and organic wastes and then transplanted in cubes of this fertile soil to the island gardens (Figure 6.6). The use of interconnected canals, crop rotation, and natural fertilization results in a simple but highly productive system (Figure 6.7). The prod-

FIGURE 6.5 Chinampa canal irrigation is augmented by manual watering. (P. Armillas)

FIGURE 6.6 Seeds for chinampa farming are started in specially enriched beds prepared from channel mud and organic wastes. (P. Armillas)

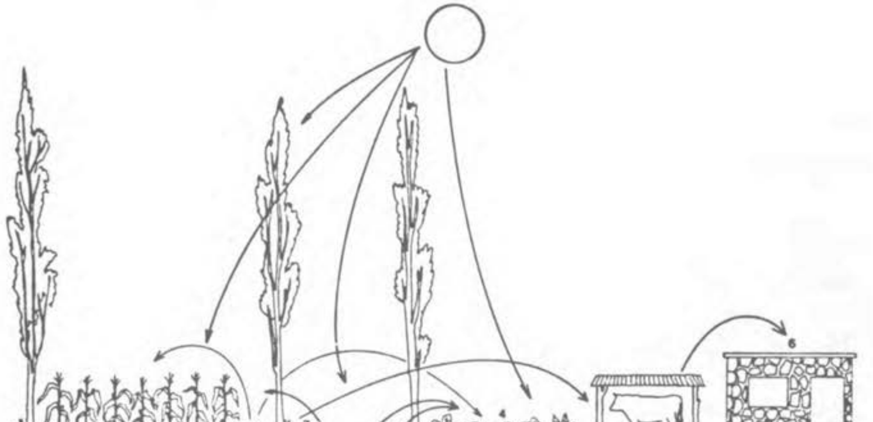

FIGURE 6.7 Continuous recycling of energy and materials in a chinampa: (1) organic soils, (2) seed bed, (3) organic mud, (4) vegetables, (5) manure from stable, (6) human food, (7) weeds.

ucts of today's chinampas include maize, beans and other vegetation, tree seedlings, and flowers (Figure 6.8). Figure 6.9, a sixteenth-century drawing of a chinampa area in Tenochtitla, Mexico, is mute testimony to the durability of this practice.

In the Philippines, Eusebio, in projecting the decreasing amount of land available per person, proposed an integrated farming system for use where space is limited. Using pigs raised in close confinement, algae ponds, a biogas generator, fish ponds, and vegetable plots, a compact unit has been suggested (Figure 6.10). Manure from the hogs and wastes from the home are used in a biogas generator to produce methane for power and light. The liquid effluent from the biogas unit is used for algae culture, fish farming, and finally for garden irrigation. The algae produced is used as part of the pig feed, and a windmill is proposed to pump the effluent. A unit to test the workability of this scheme and determine the level of management required will be built in the Philippines.

An even more compact unit has been suggested by Golueke and Oswald (Figure 6.11). The design was devised on the basis of a single family unit (four persons) plus one cow and fifty chickens. The system includes biogas generation, algae production, and rain collection. Algae in slurry form is fed to the cow and constitutes its sole source of drinking water to force consumption of the algae in wet form. Slurry not consumed is dried on sand beds and fed to the chickens. All human and animal wastes are fed to the biogas unit to provide fuel and biogas liquid effluent used for algae culture.

Hillman and Culley proposed an integrated dairy operation using the manures for biogas generation and the generator effluent for raising duckweed (Figure 6.12). Citing several species of duckweed that have proved nutritious as food or feed and the ease of harvesting species of this floating plant, they suggested the use of duckweed to treat the effluent from the biogas unit and provide part of the cow feed. Overflow from the duckweed lagoons could be used for fish culture and irrigation.

Chen and Day have described the parameters for ethanol fuel production in an integrated farm system. Biogas from cattle or swine manure is used to power an ethanol production unit. Ethanol is used to power farm equipment. Maize, partially fertilized by the effluent from the biogas unit, is grown for use as a substrate for alcohol production, and by-product stillage is fed to the livestock (Figure 6.13).

Large-Scale Integrated Systems

Kaplan Industries (Bartow, Florida, USA), faced with disposing of 500 tons/day of manure from a 20,000-head cattle feed lot, initiated a large-scale program of waste utilization. About 40 tons/day of the solid material in the

FIGURE 6.8 Maize and other vegetables are grown on this chinampa in Tlahuac, D. F., Mexico. (P. Armillas)

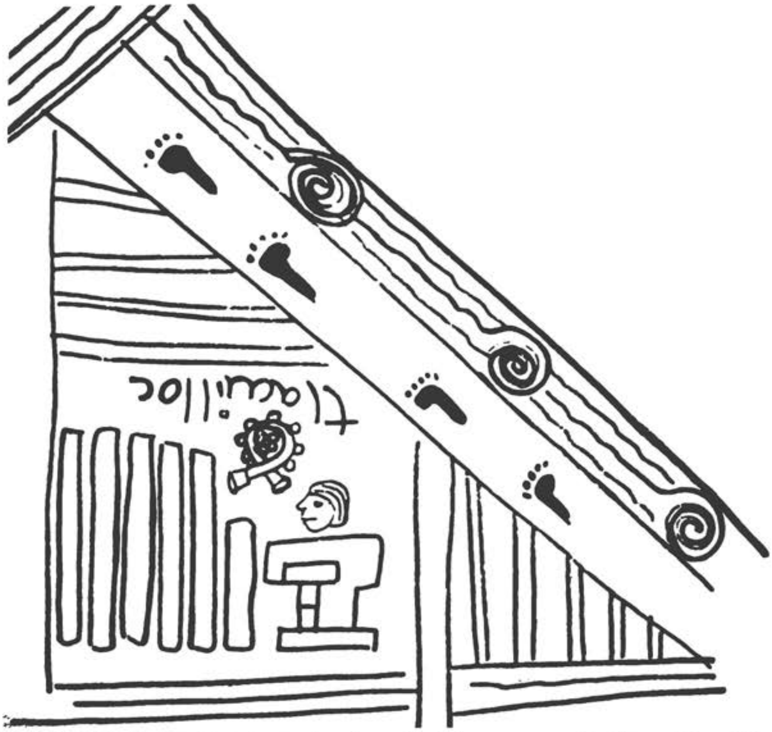

FIGURE 6.9 Sixteenth-century drawing of chinampa area in Tenochtitla, Mexico. (from the Codice Papel Amati)

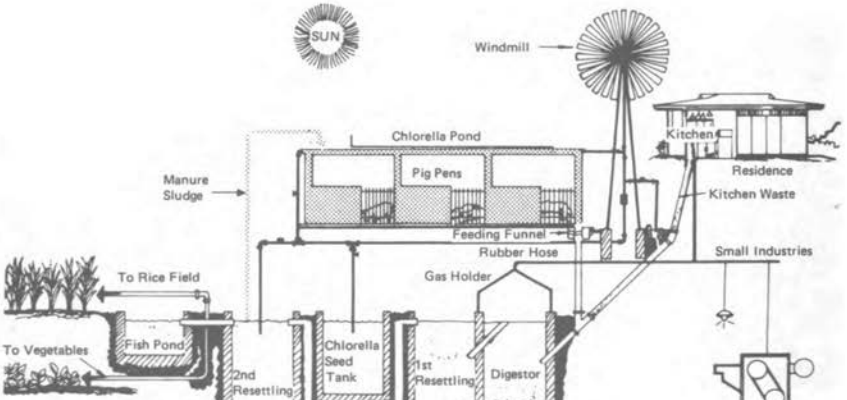

FIGURE 6.10 A proposed integrated system, including pigs, fish, biogas, *Chlorella*, and vegetables. (J. Eusebio)

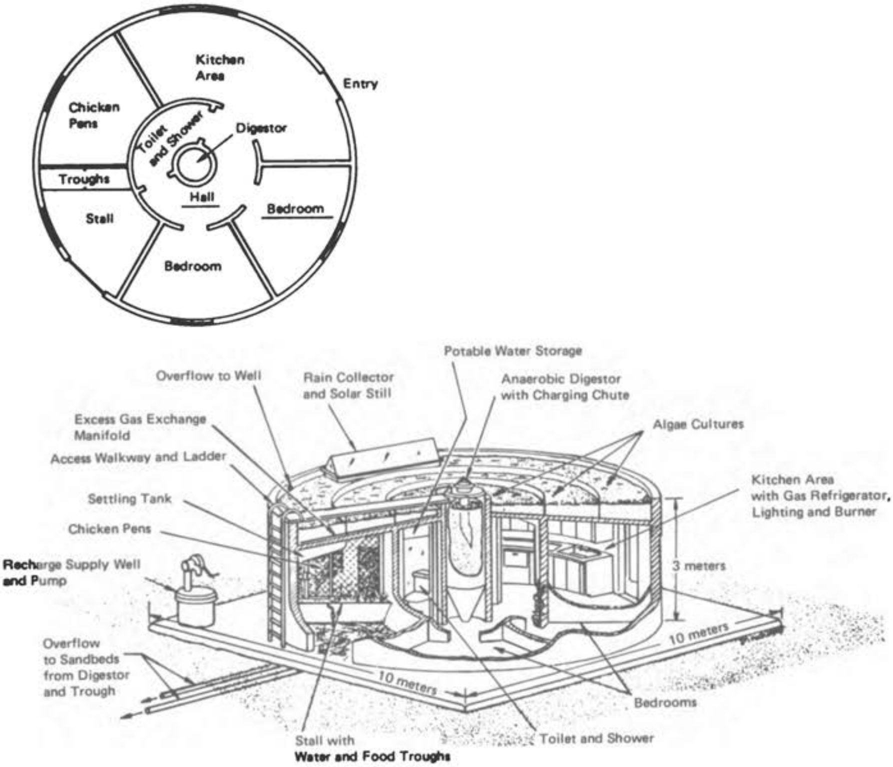

FIGURE 6.11 A proposed dwelling unit for a family of four and their livestock with a recycle system for water, nutrients, and energy. (C. Golueke and W. Oswald)

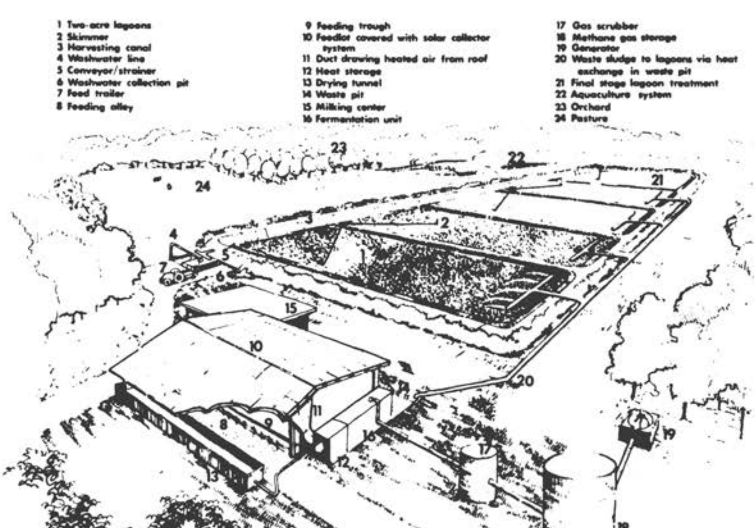

FIGURE 6.12 An integrated dairy farm based on the culture of duckweed. *Source*: Hillman and Culley, 1978.

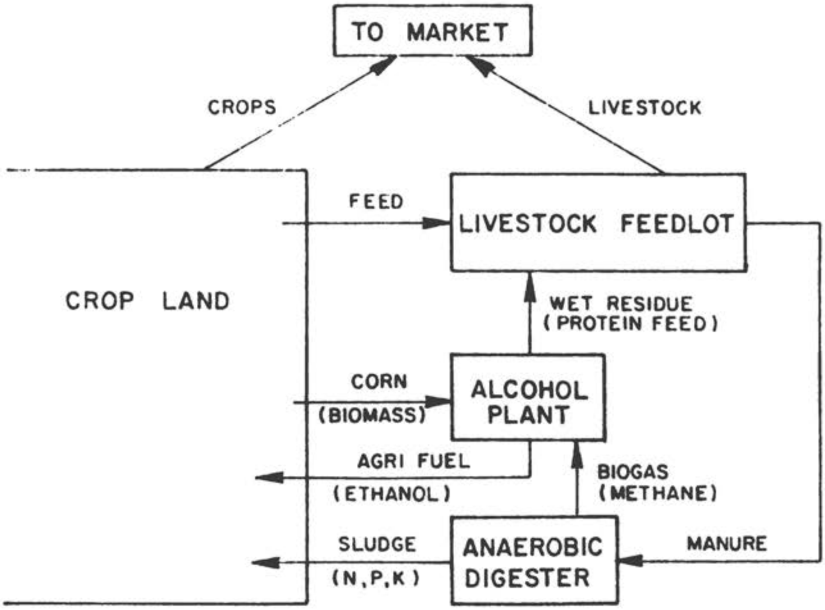

FIGURE 6.13 Integrated farm fuel system.
Source: Chen and Day, 1980.

manure is separated and recycled as part of the feed. The liquid portion with some suspended solids is transferred to a biogas generator that provides fuel for the adjacent slaughterhouse. The biogas generator sludge is centrifuged to yield 20 tons/day of a 50-percent protein product that can be used as a feed supplement. The liquid effluent from the generator is passed through a series of anaerobic and aerobic treatment lagoons. Algae growing in the aerobic lagoon provide food for tilapia. Part of the effluent from these ponds is chlorinated and returned to the cattle as drinking water, and part is used to irrigate corn, sorghum, and oat crops used as feed.

A large-scale project in Thailand encompassing a rice mill and an agriculture-aquaculture complex has been described by the UNEP regional office in Bangkok. The M/S Kamol Kij Co. Ltd. in Panthum Thani Province produces about 450 tons/day of parboiled and polished rice from purchased paddy. The by-products and co-products of rice processing are used in the production of pigs, poultry, eggs, fish, vegetables, bricks, bran oil, and energy (Figure 6.14).

Although most of the broken rice produced in the milling operation is sold, a portion is used as feed for the chickens, ducks, and pigs. In addition, after solvent extraction to produce rice bran oil, the defatted rice bran is used as feed.

Rice husks are burned to produce the energy needed for parboiling, dry-

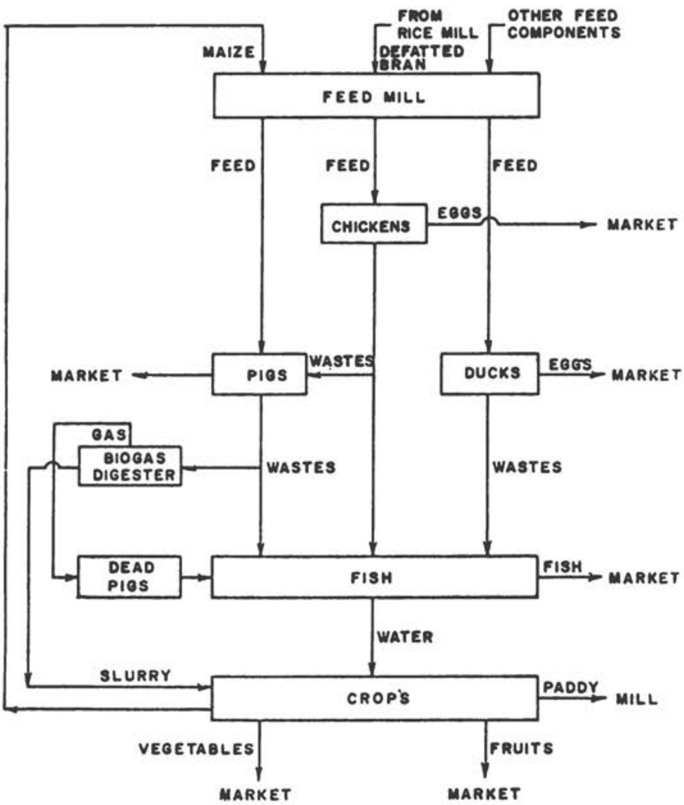

FIGURE 6.14 Schematic of M/S Kamol Kij Co., Ltd., Farm, Thailand, in which livestock, crops and fish are integrated.
Source: UNEP, 1979.

ing, and oil extraction. Part of the incompletely incinerated black ash from husk burning is mixed with clay to make bricks and part is used to fire the brick-making kilns. The white ash from the kilns–almost pure silica–is sold for use in insulators and abrasives. Waste heat in the flue gases is also used for drying paddy.

About 6,000 chickens, 7,000 ducks, and 6,000 pigs are maintained. The chickens and ducks are reared, sold, and replaced on a 2-year cycle, and the pigs every 6 months. About 1.4 million chicken eggs and 1.6 million duck eggs are sold each year.

The chicken coops are located above the pigsties so that wasted food and droppings are consumed by the pigs. Crop wastes provide additional pig feed. Some pig manure is used in a biogas unit to generate heat for cooking pigs (that died before marketing) for use as fish feed. The remainder is used to fertilize fish ponds where tilapia, clarias, and pangasius are cultured.

About 16 hectares of duck and fish ponds produce 24 tons of fish each year. Fish pond sludge and biogas sludge are used as fertilizer in the vegetable gardens. Maize, bananas, pineapples, and other crops are produced and sold.

Maya Farms in the Philippines is another example of a successful integrated agroindustrial operation. This 24-hectare complex (Figure 6.15) maintains 15,000 pigs, marketing nearly twice that number annually. Every day, 7.5 tons of manure is fed into each of three biogas generators. These 500 m^3 units are operated on a continuous plug-flow regime with a retention time of 25 days. The 400 m^3 of gas produced daily by each digester is manifolded alternately into two large floating gas collectors (Figure 6.16) and used on the farm for powering deep-well pumps, slurry pumps, a feed mill, and refrigeration units of a packing plant. At night, surplus gas is shunted to electric generators.

The liquid effluent from these digesters is fed to fish ponds, where the resulting algal blooms support the growth of tilapia. Digester sludge is used as a partial ration (10 percent) in the pig feed, reducing feeding costs and producing slight increases in growth rate.

In the People's Republic of China, the Xinbu Brigade of the Leliu Commune in Guangdong Province is working toward self-sufficiency through an integrated farming process. Their rural production system involves and largely supports about 89 families. Fish, pigs, sugarcane, bananas, and silk are produced for sale. Much of the energy and fertilizer required is recovered from animal, human, and agricultural wastes (Figure 6.17). Some chemical fertil-

FIGURE 6.15 Maya Farms in the Philippines raises pigs (sheds in background) and tilapia (ponds in center) in an integrated system. (E. Lincoln)

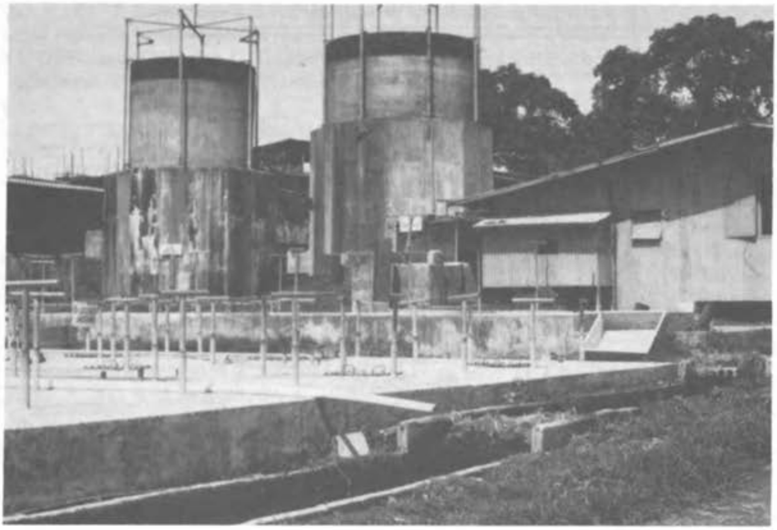

FIGURE 6.16 Biogas generators (foreground), each with its own stirring device, feed gas to the floating-top tanks at Maya Farms. (E. Lincoln)

izer, fodder, and night soil from outside the community is used.

Four species of fish are raised in 18 hectares of ponds scattered through the community. Silver-, bighead-, and grass carp feed in the middle and upper layers of these ponds, and dace (*Cirrhina molitorella*) scavenge the bottoms. Annual fish yields average about 4,400 kg/ha. Pond sludge is used for crop fertilizer.

Mulberry bushes are grown on the slopes of the dikes surrounding the ponds. Mulberry leaves are fed to silkworms and the silkworm droppings fed to the fish. The cocoons are dried, using waste heat from the biogas-powered electrical generator.

Pigs consume kitchen wastes, napier grass, water hyacinth leaves, and purchased fodder. Their wastes are used in biogas production.

Almost all of the families have individual biogas units and seven other digestors are operated on a communal basis. The gas from the family units is used for cooking and lighting. The communal digestors power an electricity generator for electric lights and a pulverizer. Liquid effluent from the digestor is added to the fish ponds and the sludge is used on the field crops.

Limitations

There are two prime limitations for the broader use of integrated systems: the most obvious is that the investment required for such systems is signifi-

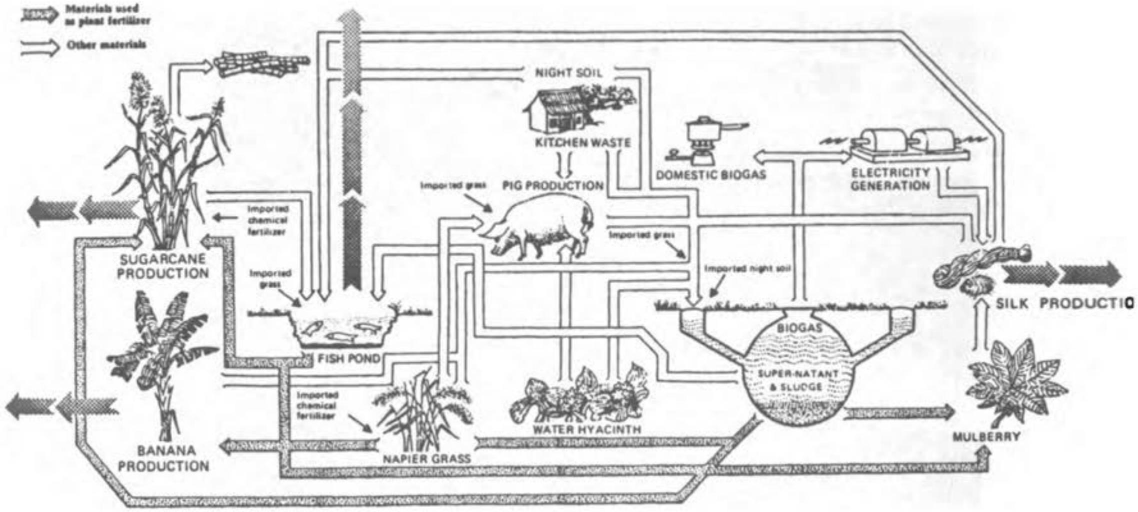

FIGURE 6.17 Fish, pigs, sugarcane, bananas, and silk are produced on this integrated farm in rural China. (*Development Forum*)

cantly greater than for less sophisticated operations; the second problem involves the diverse training and intense maintenance required to establish and operate such a system. With some systems described in this chapter, a simple leak or pump failure could cause extraordinary problems.

Research Needs

Basic information is needed on step-by-step approaches to integrated systems appropriate for small landholders. Data on traditional integrated systems in South and Southeast Asia would be particularly helpful.

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7 Nontechnical Considerations

The feasibility of waste utilization projects depends not only on factors such as physical resources and needs but also on public health, economic, and institutional considerations. In addition, cultural mores may control strong preferences or taboos concerning certain alternatives. Before new techniques are employed, they must first be understood and then seen as socially acceptable. Otherwise, interventions focused purely on technology–whether indigenous or foreign, new or old–may be destined for failure. Standard methods of project analysis will generally be deficient because they often emphasize readily quantifiable variables. Thus, for example, when an economist translates technical elements into economic values, he must be alert to social, cultural, and institutional factors, whether or not economic values can easily be assigned to them. Some of these aspects are discussed below.

Public Health

In many developing countries, poor environmental conditions such as inadequate and unsanitary water supplies, unsanitary excreta disposal, reservoirs of insect vectors, and lack of health education can be responsible for high morbidity and mortality. This is especially true among poorer groups of the population in both rural and urban areas.

When human and animal excreta or municipal sewage is used, directly or indirectly, for the production of food, feed, or fertilizer, it is essential to consider health implications. Unsanitary practices when handling these materials can result in the spread of diseases or in debilitation caused by toxic substances. Waste utilization processes, therefore, must be carefully monitored for adverse impacts.

Domestic sewage contains a complete range of pathogenic organisms found in the community, including bacteria, protozoa, viruses, and parasite ova. It may also contain heavy metals and organic and inorganic compounds from industrial activities or from the application of fertilizers and pesticides. The concentration of these materials in the waste and the method of waste utilization will determine the degree of risk involved.

Experience has shown that domestic wastewaters can cause public health problems if proper standards of hygiene are not part of waste utilization efforts. Organisms causing typhoid, dysentery, and other protozoan and helminthic diseases can be found in raw sewage and treated sewage effluents. The contamination of vegetables irrigated with sewage is the likely cause of epidemics of these diseases in several instances. Individuals working with raw or partially treated sewage can be more heavily infected with hookworm and suffer more intestinal infections than others in the same community. Cattle grazing in sewage-treated pastures can become infected. Fish and crustacea in aquaculture projects using domestic wastewaters can be contaminated. Schistosomiasis propagation through infected feces and urine is a particular concern in some areas of the world.

Although much of the pathogenic load of bacteria and higher organisms in sewage can be removed by conventional wastewater treatment processes, viruses are less susceptible and are resistant to chlorination in normal doses. Therefore, special precautions must be taken when wastewater utilization is considered. Hepatitis is a particular hazard. Although hepatitis microorganisms have not been isolated, there is evidence that they can be transmitted through contaminated water and aquatic life such as oysters.

The strongest negative factor in the use of human and animal wastes for the production of food, feed, or fertilizer is the possibility of disease transmission, which would negate the gains derived from the use of the waste.

With increased discharge of industrial wastes into sewage systems, levels of heavy metals and toxic substances in municipal wastewaters and streams are increasing. Because fish and other elements of the human food chain can concentrate such substances in their tissues, consuming them can result in human illness.

These public health concerns can be overcome by proper management of hygienic methods and need not prevent waste utilization. However, the importance of proper management in any waste utilization project cannot be overemphasized.

Economic Aspects

Project Analysis

When considering the feasibility of multipurpose projects with several outputs (for example, an excreta disposal project that produces biogas, compost, and cattle feed), the economist will attempt to establish the best mix of resource disposal, resource use, and resource recycling, which will involve the translation of technical constraints into economic values. For example, the use of oxidation ponds and fishponds as a resource recovery system depends greatly on land, and this must be valued at opportunity cost. Similarly, output values must be realistic within a given socioeconomic environment. If fish produced in wastewater are not marketable, they have no value, and alternative technologies, such as fishmeal or algae production, should be substituted in the feasibility analysis. The benefits and limitations of labor-intensive technologies should also be considered. Resource technologies can be designed for intensive use of manual labor, providing extra benefits in an economic environment where there is underutilization of labor or high unemployment.

Integrated Project Analysis

Evaluation of waste utilization projects is not always straightforward. Integrated projects, which involve the collection, treatment, and reuse of human, industrial, and/or agricultural wastes, are particularly difficult to evaluate. One problem arises because of the single focus of some project evaluations. Because these projects by their nature involve linkages among and across sectors, their full costs and benefits will not be captured if the framework of the evaluation is too narrow.

A second evaluation problem arises when the linkages between the project and its environmental or health benefits are poorly understood and difficult to quantify. When environmental or health benefits are the major justification for a project, it is a serious impediment to the use of the normal project evaluation procedures.

A third problem is that some benefits materialize only gradually. It may take many years to reverse a process of environmental decline. However, it is difficult to extend economic techniques, which involve the discounting of future values, to cover cases where benefits are deemed important regardless of when they accrue.

Project Optimization

There are two further conditions that must be met for a project to be socially optimal. A biogas unit that may not be economically viable on its own as an alternative to other fuel sources may become feasible if it is integrated in a waste disposal project. Moreover, it might be the *optimal* waste treatment option (because of the energy benefits it produces) although not perhaps the least costly.

The benefits of waste utilization projects are obvious. They make productive use of waste material usually considered a nuisance to be eliminated at lowest cost. Although these projects may not in themselves provide sufficient benefits to make them economically attractive for entrepreneurs, they may substantially reduce public health and environmental problems and the cost of waste disposal, thus contributing significantly to the overall well-being of the community.

Community Waste Disposal

The conventional human waste disposal method used in industrialized countries is waterborne sewage. The most significant advances have been made during times of greatest economic progress by the two countries most responsible for the universal adoption of waterborne sewage–England during the height of its imperial power and the United States during its industrialization. It was during these periods that improved waste disposal became an urgent need and the resources for the construction of sewer systems were available.

In industrialized countries, sociocultural aspects did not create significant problems in the implementation of sewerage schemes, owing probably to the convenience of flushing waste down the drain and letting others worry about ultimate disposal and also to the fact that such systems were paid for by the government. Further, the ultimate cost of treatment and the dangers to the environment were not known. Although no religious, cultural, or social taboos existed to reduce acceptance of the sewerage method, in some areas resistance to changing individual behavior patterns persisted.

In developing countries the situation is somewhat different. Sewerage is expensive and funds are not available to make it a universal solution. Its application is generally restricted to the densely populated core of major cities. Interestingly, even where waterborne sewerage is available and connection mandated by law, it is not unusual to find even after many years that less than half of the households are connected. The apparent cause is lack of funds, but cultural aspects may play a role as well.

While there may be acceptance of sewers, other methods of waste disposal can be subject to strong preference–or rejection–on the basis of sociocultural preferences. Examples are numerous: the use of the same facilities by different ages or sexes may not be acceptable; preferences for certain types of physical structures (including color) may exist; or the desire for privacy or, in contrast, the wish to be able to communicate with others can also be a factor.

Similarly, the reuse of waste material evokes strong reactions based on sociocultural preferences. Human excreta is common as a fertilizer in some cultures and totally unacceptable in others. This prohibition against using human excreta can even extend to a prohibition against the use of biogas generated from excreta. Interestingly, the same cultures consume fish from waters containing human excreta, and do not find the use of animal excreta offensive, nor do they prohibit the use of sewage sludge or composted excreta on their crops.

Project Development

The developer of waste disposal and utilization systems must recognize the sociocultural aspects that can affect user acceptance of the proposed system.

The developer must not only identify sociocultural constraints but also seek community participation in the selection and design of waste disposal and utilization approaches. Community participation in the evaluation of alternatives and selection of the preferred solution also provides an excellent opportunity for education on health and other benefits to be derived and on the financial implications of constructing, operating, and maintaining the system. The better informed the community is and the closer the project matches the users' perceived needs and preferences, the more likely the project will succeed.

This approach to project development and implementation is not ordinarily practiced in industrialized countries where the usual procedure involves massive intervention by centralized institutions. Development concentrates on the technical/financial aspects that can be competently handled by engineers, financial analysts, and economists. In contrast, owing to the sociocultural constraints that must be considered, waste disposal and utilization projects in developing countries usually benefit from participation of behavioral scientists and educators on the development team. Indeed, success of the project requires their input.

Without adequate community participation, waste utilization projects may fail because the community fails to undertake the necessary operation and maintenance. On the other hand, with community participation, such projects can solve waste disposal problems with costs substantially lower than those of conventional sewerage and can offer the best, and possibly only, hope for providing a solution to human waste disposal problems in developing countries.

A creative solution to this type of community sanitation problem has occurred in India, where approximately 40 percent of the population in large cities does not have access to basic services such as clean water, latrines, and health services. Many of these are pavement dwellers and do not have even the semblance of a conventional shelter. With no access to sanitation and health facilities, this group must resort to using public spaces and roadsides as latrines. This presents a serious hazard to public health. Although city authorities provide community facilities such as latrines and bathing places, these facilities are almost always inadequate for the size of the population. In addition, the maintenance of these services is ineffective and costly and results in dysfunctional services inefficiently operated.

In 1973 a nonprofit, nongovernmental organization was established to improve this situation in Patna, the capital of Bihar, and in other cities in the state. The name of the group is Sulabha Shauchalaya Sansthan (Simple Latrines Agency). This agency requested the city to transfer the communal sanitary facilities to them. The agency now maintains and supervises these services, and the city is free of this function and its expenses. The agency does not charge the city for maintenance of these services but does charge a fee of 10 paise (2 cents) per person for use of the latrines. Half of this amount pays for soap for washing. The bathing and urinals are free of charge. All services are free for women, children, and the poor.

The maintenance functions are carried out by a staff that operates on a round-the-clock, 8-hour-shift basis. In Patna alone there are more than 2,500 public latrines, baths, and urinals at more than 200 locations. The daily amount collected by way of charges is approximately 5,000 rupees (or $550).

This agency also constructs simple latrines for individual families under the latrine conversion program of the state government. In most of the urban areas, where conventional bucket-type latrines exist, the government provides a subsidy and loan to individuals to convert to a water-seal type of pit latrine. The agency takes complete responsibility on behalf of individuals to secure loans and subsidies and constructs latrines with a 5-year warranty. The agency charges 10 percent of the construction cost as its fee for this service. It has built thousands of latrines in Patna and other towns under this program. The latrines are simple and cost approximately 400 rupees ($50). The sludge from the pits is used as garden or farm manure.

The agency employs more than 1,800 staff and has a turnover of more than 5 million rupees per year ($500,000). It does not accept any grants or subsidies for its work.

Institutional Aspects

Technical Assistance Needs

Technologies for waste utilization are generally well known. There are enough of such technologies available to allow a selection to suit the specific requirements of almost any community and environment. Although sociocultural evaluations are becoming a more accepted part of project development, many projects still fail owing to the lack of adequate institutional arrangements.

Institutional support is needed to assist communities in tasks they cannot undertake themselves, including marketing services for the sale of resultant products, interim financial support, management guidance, and the like. The community may need assistance in purchasing necessary components to enhance a product's marketability, such as addition of phosphate or nitrogen to enrich compost, or to produce a more profitable item, such as vegetable crops rather than grain if the project is located near a city. Another form of assistance may be helping a community establish an organization to operate and maintain waste disposal and waste recovery enterprises. Another need is technicians to repair equipment where local maintenance is unable to manage the task. Often there is a need to establish a central source for needed spare parts. Frequently, local manpower may be capable and often ingenious in making repairs, but if the technology requires replacement parts not available locally, the system may fail. Finally, for some systems, special training may be required to provide technical skills beyond those available locally, particularly for systems that involve sophisticated equipment.

Although the need for institutional support and training is generally accepted, the desired approach may not be clear because relevant experience is scarce and often inconclusive. Waste disposal systems in industrialized countries are highly centralized, use sophisticated technologies, and may not be suitable or economical for most of the medium-size and small communities in developing countries. Other technologies using highly site-specific disposal solutions rather than centralized systems are also often not encouraged because they require different institutional managements that neither are well defined nor have a successful history. However, if progress in waste disposal and waste utilization is to be made in developing countries, the temptation simply to adopt institutional methods successful in industrialized countries should be resisted. Given the relative scarcity of trained personnel to manage centralized systems, a large number of small site-specific individual or small-community operations appears to represent a more stable system. In such a system a failure of any part is isolated, with a relatively small impact on the environment, and can be more easily repaired than the failure, for example, of a municipal garbage collection system or sewage treatment plant that has a serious and immediate impact on the environment and the community.

Institutional Models

While no universally applicable institutional format exists, one possible solution is the three-tier system that has been successfully employed in some rural water supply projects in India. The system consists of a central technical support unit that provides engineering, hydrogeologic, and well-drilling expertise, and spare parts warehousing, mechanics, and other expertise not within the competence of the village. In the village a caretaker maintains the water supply system with the help of the technical support unit. Most important, there is a link (the middle tier) between the support unit and the village. This link is a roving maintenance supervisor capable of routine repair work and analysis of deficiencies he is unable to correct himself. This system is one possible approach to providing support and technical assistance to communities and it is a relatively simple solution.

In the waste disposal and utilization sector, other inputs, already described above, are necessary. Other disciplines may be needed, such as the behavioral sciences, which may not be available in the government agency responsible for waste disposal and utilization. This results in the need to establish a multidisciplinary unit with coordination among various departments. One possible solution is the use of nongovernment or private voluntary organizations to assist communities in project development. These groups are often able to field multidisciplinary teams that are not subject to restrictions resulting from jurisdictional disagreement between two or more interested agencies.

Institutional arrangements must encourage maximum community participation. Decentralized systems are usually best. At the same time, however, central technical assistance and support must be provided. The correct balance is not easy but is essential for success. The familiar centralized waste disposal systems and management are not applicable to rural and small town environments, especially in integrated waste disposal and utilization projects.

Socioeconomic Aspects

Socioeconomic limitations result, in part, from assumptions concerning man's readiness to adopt new ideas. If a waste utilization technology is to be disseminated readily, the presumed beneficiaries of the technology must, in their own judgment, feel that this technology is applicable to and will benefit them. Uncertainty about how best to disseminate new technology in developing countries makes it impossible to know in advance whether a technology will actually be used.

Clearly, no technology is appropriate for all people in all circumstances. An appropriate waste utilization technology may require the availability of irrigation facilities or a continuing supply of a given waste. An appropriate technology for landholders will not be appropriate for those who have no land. Each waste utilization approach must be tested and examined under widely varying local and regional conditions. These conditions have to do with more than the physical environment in which the technology is to be introduced. Among the questions to be considered in an agrarian society are:

- Who owns the land, the ponds, and the equipment?
- Who tills the land for whose benefit?
- What are the present and alternative uses for all the process inputs, including the waste?
- Has the role of women as decision shapers (if not decision makers), trainers, and socializers been considered?
- Will significant changes in individual behavior or social structure be needed?
- Will the introduction of any new technology require external subsidies?
- What institutions can provide these subsidies if they are necessary?
- Who will be the beneficiaries of the products of the new technology?
- Who will be nonbeneficiaries?
- If the nonbeneficiaries are in the majority, what are the political im-

plications of introducing a technology that benefits the few, rather than the many?

- Is there danger that the technology widens income inequalities that are already a feature of many countries?

These questions are raised to emphasize that no technological innovation, least of all one that has not been widely disseminated and tested in the field, will be appropriate for all situations or all people. Finally, because the introduction of new technology may be a culturally disruptive process, those who implement the technologies should do so with a clear recognition that the adaptation of ideas or models in widely divergent physical, social, economic, and political circumstances will require no less of an innovative spirit than the generation of the initial concepts.

Conclusion

The development and utilization of waste reuse technology will require an extraordinary degree of coordinated effort among persons and agencies having a variety of skills and capacities. Quite apart from the technological aspects of waste utilization projects, there are public health, economic, institutional, and cultural dimensions that must be addressed if such projects are to be successful. It is no detraction from the potential of any project to emphasize that it must be more than technically feasible to be implemented.

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