REVIEW

Environmental Engineering: Energy Value of Replacing Waste Disposal with Resource Recovery

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Although in the past, environmental engineering has been primarily concerned with waste disposal, the focus of the field is now shifting toward viewing wastes as potential resources. Because reclamation usually consumes less energy than producing new materials, increasing reclamation not only reduces pollution but saves energy. Technological innovations contributing to this shift are summarized here, and are variously classified as emerging technologies or research topics, as either new departures or incremental improvements, and as opportunistic innovations, or examples of a unifying strategy. Both liquid and solid waste examples are given, such as a recent discovery of effects in disinfecting microfiltered reclaimed wastewater with ultraviolet light. In addition to its value in reducing pollution and conserving energy, this reorientation of environmental engineering could contribute to a more general shift toward greater cooperation among organizations dealing with the environment.

All human endeavor interacts with the environment, yet environmental engineering has been carried out in relative isolation from the rest of society. It has been understood as the field that develops technologies for waste disposal and builds and operates facilities implementing these technologies. The principal concern has been to dispose of wastes in the most convenient and least expensive way, without attempts to convert them into useful substances, and with little interaction between disposal agencies and the organizations, and populations that produce the wastes.

There is now a growing recognition that neither wastes nor resources are rigidly defined concepts, but rather depend on customs or values (real or perceived) and on available knowledge and technology to determine whether a substance is considered potentially useful, hence a resource, or useless at best, and therefore a waste. With greater understanding or ingenuity, it may be possible to process useful components from what had previously been considered entirely useless waste streams.

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Such waste reclamation has several potential benefits. One is to reduce consumption of what have traditionally been considered "natural resources," such as ore minerals and fresh water. Another is to reduce pollution produced by discharging untreated waste. Still another is the energy conservation effect of reclaiming wastes.

The basic principle emanating from existing reclamation industries is familiar: producing useful materials from natural resources often requires large amounts of energy and may impose additional costs for transportation from where the resources are available to where the product is used. Additional energy may be needed to treat wastes to make them safe for disposal and to transport them from collection or treatment centers to disposal sites. All of this energy is lost when the waste is discarded. On the other hand, there are many materials for which the energy costs of reclamation are a small fraction of the costs of new production. The steel and aluminum scrap industries were established long ago because of such considerations, but it now seems desirable to take into account the energy value of waste reclamation in cases where the disparity in energy consumption between production and reclamation is not as extreme.

Admittedly, the energy benefit expected from additional waste reclamation is modest in many cases compared to the benefits expected from other improvements in the efficiency with which energy and materials are used. In particular, there are great hopes for several energy technologies that are not widely used now, but that have been under investigation for many years, such as fuel cells and magnetohydrodynamic devices. Also, there are continuing efforts to use waste heat from high-temperature industrial processes, like power generation and metal smelting. Nevertheless, waste reclamation deserves to be a part of the overall energy picture, and in some cases, such as reclaiming wastewater instead of desalinating ocean water for southern California, the total expected savings may have substantial local or regional economic importance.

Thus, instead of simply reacting to governmental and public ideas about wanted or unwanted materials, environmental engineering has a challenge to become more active and seek new methods of separation, conversion, and reclamation. Because many economic, legal, and social debates over environmental issues occur within frameworks of assumptions about technical feasibility, this article focuses on some novel processes and operations (*1*) on wastes that promise future increases in the range of technical options available to practicing environmental engineers.

A vast range of innovative processes and operations is currently under investigation, from technologies that have already achieved some degree of commercialization to possibilities that are presently only speculative. Some can be viewed as examples of a unifying strategy, and some are opportunistic innovations that take advantage of scientific facts or conditions without further generalizations. Implementation of some of these innovations would lead to incremental improvements in existing activities, and some would be new departures in waste treatment or resource reclamation.

Emerging Technologies

Novel technologies that have already achieved some degree of commercialization may for convenience be called emerging technologies, and they are prevalent in types of waste reclamation that are already well established, such as wastewater reclamation. The following is an example of an unexpected phenomenon that has been observed when two well-studied emerging technologies were combined.

Microfiltration and ultraviolet disinfection in wastewater reclamation. Wastewater reclamation is already being practiced in many places, although generally on a small scale and in applications where the public is protected from any remaining pathogens or contaminants that may be present, such as crop irrigation or recharge of depleted aquifers (*2*). Since increased quantities of wastewater will be reclaimed in the future, as populations continue to increase and natural water supplies in many places remain fixed, standards have been established for more health-sensitive forms of reuse, all the way to direct reuse as drinking water (*3*). These regulations are already very stringent and may be tightened further to relieve public apprehension about toxins and pathogens that have prompted political restrictions on water reuse. It is now possible, but expensive, to treat wastewater until it is cleaner than natural supplies, as in a recent test at Lake Arrowhead, California (*4*), a lake that is locally famous for its purity. Even where additional water supplies are available, the energy costs of pumping them from great depths or large distances may make reuse preferable.

Ultraviolet (UV) disinfection has emerged as an alternative to disinfection with chlorine or chlorinated compounds in reclamation, and preceding UV disinfection with microfiltration provides several benefits: (i) it greatly reduces the turbidity of the effluent; (ii) it removes bacteria and other organisms that are too large to fit through the pores; (iii) if the UV disinfection unit is a low-pressure, low-intensity unit, microfiltration reduces fouling (low-pressure units are the only ones subject to fouling, because medium-pressure units not only incorporate a self-cleaning brush system but operate at such a high intensity that bacteria do not grow on the lamp sleeves (*5*); and (iv) it reduces introduction of chlorinated byproducts into the environment (*6*).

Moreover, evidence has recently been found (*7, 8*) that microfiltration greatly reduces the UV dose needed to achieve mandated levels of virus inactivation (*3*). This is consistent with expectations, since microfiltration removes most of the particles that could scatter incoming light or provide shelter for viruses, and the standard was based on experiments with secondary effluent that had not been microfiltered.

Furthermore, UV disinfection provides an example of how careful attention to details of a process may lead to additional improvements in efficiency. This suggestion is prompted by the description (*7, 8*) of a low-pressure UV disinfection system that shows an apparent substantial departure from the first-order kinetic theory of virus inactivation, which has been heavily supported by both general physical and chemical considerations and experimental evidence accumulated over many years (*9*). A plausible explanation of this observation is that it is the result of hydrodynamic effects that invalidate the simple formula by which Jolis and Hirano (*7*) estimate their doses (*10*): boundary layers form around the lamps and the sides and bottom of the channel, with the thicknesses of these layers increasing with decreasing flow in a way that provides near constancy of actual exposure time for most of the water in Jolis and Hirano's test. Because boundary layer formation is supported by basic theory (*11*) and direct observations in a similar but larger UV disinfection channel (*12*), and is consistent with small departures from plug flow observed in a detailed hydrodynamic study of a channel that is very similar to Jolis and Hirano's apparatus (*13*), two conclusions are justified: (i) the actual dose to most of the water was below Jolis and Hirano's estimates, promising further energy savings in disinfecting microfiltered water, and (ii) the design of UV disinfection units could be modified with small vanes along wetted surfaces or other measures to more closely approximate plug flow at low speeds by suppressing boundary layer formation (*10*). Figure 1 shows a hypothetical configuration. This geometry would improve the dose estimate and the energy efficiency of disinfection, by allowing some UV lamp banks to be turned off when flows are low.

Online biological oxygen demand monitoring. Another emerging technology that is potentially applicable to wastewater reclamation is online monitoring of biological oxygen demand (BOD) for improved control of the primary and secondary treatment in a reclamation plant. Recently, several manufacturers have begun offering automatic instruments containing a supply of microbes and an oxygen concentration monitor, so that the nutrients in a sample of wastewater are consumed in a few minutes, with determination of the corresponding oxygen uptake

(*14*). These measurements substitute for the long-established standard test, which spends 5 days waiting for natural biological oxidation (*15*). The results from these instruments correlate well with the standard test for municipal wastewater (*16*) as well as for other types of wastewater tested earlier (*17*).

These new instruments operate fast enough to open new possibilities for prevention of process upsets caused by unexpected biological loads and for energy-efficient operation when biological loads are lower at plants, such as the Terminal Island Treatment Plant in Los Angeles (*18*), that have to treat large and unpredictable industrial discharges. Political and economic developments probably are reducing the number of plants in the United States that must operate this way, but in many other countries, these conditions may persist for many more years.

Controlled Biodegradation: A Unifying Strategy

Not only secondary wastewater treatment but also sludge digestion are examples of a general strategy of replacing uncontrolled biodegradation in the environment (lakes, rivers, and the ocean, in this case) with controlled biodegradation under conditions that minimize harm to humans or other organisms outside the degradation system. Composting and landfills designed for gas production are other examples. These methods of waste disposal have, of course, been established for many decades, but some additional possibilities for applying this strategy have not yet received much development. A few of these are summarized below.

Termites for wood fiber degradation. Woody materials are a large fraction of the typical municipal solid waste stream in the United States (*19*). Around 40% of all solid waste is paper, and there is also waste wood, such as construction debris and broken cargo pallets. Much of this waste wood is not suitable for processing into paper. Moreover, paper fibers can only be recycled a few times (*20*), and unlike, for example, aluminum beverage cans, they cannot be reused in material of constant quality. Hence, there is a large supply of wood fiber material that has no present use except incineration or burial in landfills.

Controlled termite colonies might provide an alternative, by analogy with the biodegradation tanks in wastewater treatment. Termite feeding produces the mechanical fragmentation of the fibers needed for rapid bacterial decomposition, and the termite digestive process releases methane (*21*) so that a suitably enclosed colony would allow collecting it for fuel. This would be analogous to present systems that collect methane from sludge digestion or from closed landfills. It may also be possible to harvest the biomass of the termites for fertilizer or as a source of protein for animal feed or chemical processes. This possibility appears somewhat speculative now, but we have recently learned of an Israeli study that fed newspaper to termites. Additional work would be needed to determine feasible fiber consumption rate, methane and biomass production rates, and the design of a suitable enclosure. Possible toxic effects of residual chemicals left from paper-making or chemicals that might be encountered in construction waste or cargo pallets are also unknown. The Israelis found that substantial wet residues were produced, so that a termite system might need something like a wastewater plant sludge digester and probably would need to be part of a larger solid and liquid waste treatment complex. Considering the worldwide importance of termites in cellulose breakdown and their effect on the atmosphere (*21*), investigation of ways to exploit termites in new uses of wood fiber waste appears warranted.

Acclimation of bacterial communities to degrade toxic organic chemicals. Many efforts have been made to develop strains of known bacteria to destroy particular toxins (*22*). Recent experiments (*23*) have taken a different approach that takes advantage of the biochemical adaptability that bacteria have shown in developing resistance to antibiotics (*24*). In this approach, a natural population of bacteria, almost certainly including species that have not been characterized by bacteriologists, is allowed to acclimate to a dilute solution of an organic chemical that is normally toxic to them, as well as to humans. The initial acclimation period is followed by a second period of culturing with the chemical as a sole source of carbon for the bacteria, so that it becomes a necessary substrate for their growth.

Using communities of bacteria takes into account the biochemical specialization and stepwise decomposition observed in, for example, anaerobic sludge digestion, in which acidogenic bacteria convert waste into volatile fatty acids, acetogenic bacteria convert the other fatty acids into acetic acid, and then methanogenic bacteria convert the acetic acid into methane (*25*). It also appears to produce relatively fast results, since degradation of all the toxins studied in (*23*) was observed after only a month of acclimation.

Applying such acclimated cultures to the destruction of a relatively concentrated and simple combination of toxins, such as military nerve gases or polychlorinated biphenyls (PCBs) from old electrical equipment, is an obvious possibility, but it is not the only one. Because a recent study (*26*) found that several toxic volatile organic compounds (VOCs) are unpreventably present in several California wastewater systems, addition of samples of bacterial cultures—which are acclimated to degrade the toxins—into the activated sludge of the treatment plants of these systems may reduce air emission of these VOCs.

Doing this would be analogous to the present continuous application of coagulants and polymers in the treatment process. It would require maintenance of acclimated cultures of these bacterial communities and installation of equipment to supply the culture to the activated sludge return system. If it succeeded, doing this would probably affect plant operations less than the increase in sludge biomass concentration recommended in (*27*), and would be less expensive than a permanent plant modification to cover the tanks and filter the air before discharge. There may be further unrecognized opportunities for innovative methods of culture acclimation and application of acclimated cultures to degrade unwanted substances.

Wastewater Aeration: An Innovation for Incremental Improvement

Since the surface-to-volume ratio of bubbles increases with decreasing bubble diameter, it

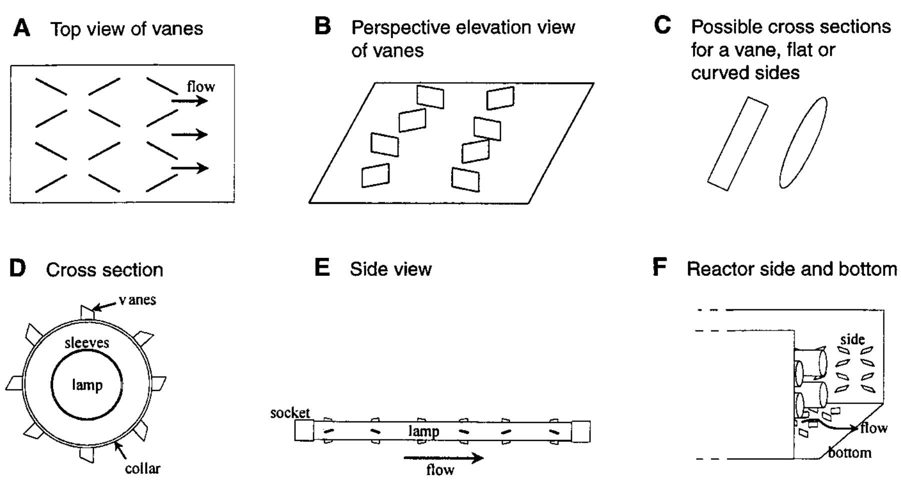

Fig. 1. Example of vane array for plug flow enhancement on lamp and reactor (not to scale).

is no surprise that the best ceramic fine-pore diffusers for conventional large wastewater aeration basins achieve efficiencies of oxygen transfer into the water that are several times higher than the oxygen transfer efficiencies (OTEs) of coarse-bubble devices such as spiral-roll diffusers (*28, 29*). Moreover, recent results (*30*) show occasional attainment of fine-pore diffuser efficiencies that are nearly double the best values reported in the 1980s (*28, 31*). Because the blowers for the aeration tanks of an activated sludge plant consume large amounts of electricity (*32*), the vastly increased use of secondary treatment (*33*), as the United States sought to meet the goals of the 1972 Clean Water Act (*34*), has been facilitated by advancing the use of fine-pore diffusers.

Located near the tank bottoms and without additional mixing, diffusers in this class produce bubbles less than 2 mm in diameter, but rarely reach efficiencies above 20%. These current ceramic technology appears ill-suited to improving this efficiency by producing bubbles smaller than a few hundred micrometers in diameter. On the other hand, a Memcor microfiltration unit (*6*) uses hollow fibers less than 1 mm in diameter, with pores 0.2 μm in diameter (*35*), and the units are automatically backwashed every few minutes by admitting compressed air to the hollow fiber interiors so that it can blow out through the pores to dislodge accumulated debris. Thus, if pressures lower than the backwashing pressure of around 700 kPa (100 psi) can be used in aeration, it may be possible to adapt microfiltration technology to produce diffusers that would directly replace the current ceramic diffusers, emitting far smaller bubbles, with correspondingly higher OTEs. The pore diameter of such a system would have to be chosen carefully to balance the energy efficiency benefits of improved OTE with the energy costs of compressing air to a higher pressure than is used in current fine-pore diffuser systems. It is likely that pores larger than 0.2 μm would be needed.

Another possibility has been under investigation for several years. Using microfiltration fibers below the bubble formation pressure allows surface tension to maintain an air-water interface across the pores, and wastewater can then be aerated by letting it flow over such fibers in devices adapted from designs used to aerate blood in heart-lung machines (*36*). Alternatively, using either microporous membranes or polymers that are permeable to oxygen, it may be possible to allow bacterial films to grow on the surfaces of other arrangements of submerged tubes carrying air or oxygen in tanks similar to those used for aeration now. Either way, the bacteria would be supplied with oxygen by diffusion through the pores or tubes instead of relying on transfer through bubble surfaces in the brief time that the bubbles rise through the water. Highly efficient oxygen usage has been achieved in research studies, but this technology has not yet come into use in full-scale wastewater systems.

Evidently, successful implementation of either of these ideas would produce an incremental improvement in current wastewater treatment technology, resulting only in a cost reduction of one process in the overall treatment system. Nevertheless, such improvements may be important in larger efforts to improve resource reclamation, by offsetting at least some of the costs of new processes or operations, such as UV disinfection.

Geothermal Pyrolysis: An Opportunistic Innovation

Unlike the general strategy of seeking controlled biodegradation, which has been discussed in a number of applications, the possibility that organic wastes can be converted into petroleum-like materials by geothermal pyrolysis is an opportunistic exploitation of several facts that presently has no evident generalization or analogy.

First, there is the long-exploited fact that heating organic materials with little or no oxygen pyrolyzes them into oily or tarry substances, with release of water, CO_2, CH_4, and other simple gases, and production of a charred residue if the temperature is high enough (*37, 38*). Next, there is the great sensitivity to temperature of both the rate of the reaction and the composition of the products (*38*). Finally, there is the availability underground of temperatures of 150°C or greater at depths accessible to drilling in many parts of the United States (*39*). Combining these facts raises the possibility that geological heat may be sufficient in many places to cause pyrolitic reaction that would produce useful chemicals from organic wastes, such as sewage sludge, if the reaction were allowed to proceed for days, weeks, or months.

This would be a less demanding use of geothermal energy than previous efforts to use natural steam for a power plant (*39*), for it demands neither as large a heat flow nor a steady supply of water. It also avoids some of the disadvantages of past attempts to use pyrolysis as a waste disposal method, which have used higher temperatures to get faster results, and hence consumed more energy in performing the pyrolysis than could be recovered from the pyrolysis products (*40*). Although solar heat would have an energy advantage comparable to that of geothermal heat, solar heat has disadvantages of daily, seasonal, and latitudinal variations in availability.

Also, although a detailed cost analysis remains to be done, solar technology suitable for building a reaction system that could provide very prolonged heat and pressure (*41*) is not as well developed or widely available as the technology of petroleum production that would be applied to drilling down to a zone of high temperature and fracturing the rock enough for the needed flow of wastes from the inlets to the outlet bores (*42*). Either form of pyrolysis would provide the world with at least a meager supply of petroleum-like chemicals that would survive depletion of the natural petroleum deposits.

Cooperation, Competition, and Adversariality

Since additional research efforts will be needed to determine whether the innovations we describe can be implemented, even on experimental or demonstration scales, one may argue that technical feasibility is no more rigidly defined than resources and wastes are, as noted in our introduction. Some of the difficulties and unknowns of the termite innovation have been mentioned, but there are also many for the wastewater innovations.

For example, clogging has been a problem in experiments on using online BOD monitoring for municipal wastewater (*16*), so that the study of the BOD-2000 included extensive tests of the correlation between measurements made on filtered samples and those made with the standard BOD test, and an automated self-backwashing microfiltration unit might be needed for operational use of these instruments. Moreover, prolonged use of a microfiltration unit with municipal wastewater requires commanding it to perform a chemical cleaning cycle every week or two, with a solution of hydrogen peroxide, citric acid, and detergent (*43*). This is significant not only for present uses of microfiltration in reclamation, but for the suggestion above to adapt the technology to aeration. The value of the aeration innovation also depends on the efficiency factor caused by the surfactants and other contaminants in wastewater (*28, 30, 44*); this efficiency factor tends to decrease with decreasing bubble size.

Moreover, as a converse to our initial comments about debates being conducted within assumptions about technical feasibility, a particular social, economic, or geographic situation may strongly influence the relevance of different technical feasibilities. For example, the public is careless enough about separating the colors of glass during recycling, so that efforts to reclaim the clear glass bottles and jars used for a vast range of food items, from baby food to vinegar, result in reclaimed glass that is a sickly greenish yellow. Many possible technical efforts to deal with this situation, such as inventing a device that could separate glass fragments more thoroughly or using reclaimed glass in glass-fiber composite materials in which the glass color does not matter, are relevant only in cases where it is necessary to gain more value from recycled glass products than what would come from, for example, substituting pulverized glass for some of the natural sand used in construction.

Likewise, it is obvious that not only glass furnaces but many other high-temperature industrial processes such as petroleum refining, metal smelting, and power generation produce waste heat at temperatures that could be used for various forms of food processing, such as bread baking, milk pasteurization, or sterilizing canned products. There have been many recommendations to use waste heat and other neglected potential sources of energy at relatively low temperatures (*45*). However, waste heat is useless for food processing if, for example, it is uneconomical to bring the food and the heat source together, or if the source is a refinery or other facility that processes toxic chemicals that risk contaminating the food.

When the success of an effort to reclaim a waste is so dependent on particular details, and substantial resources may be needed to develop a new reclamation technology, the only evident way to increase the overall rate of waste reclamation is by finding ways to exploit a large number of specific situations where reclamation can be accomplished or the efficiency of disposal improved. This conclusion argues for sometimes going beyond established patterns of research focused on a relatively few industries that have such large special waste processing needs that research programs have grown up to address them (*46*). There may be value in additional studies comparable to those reported in this article, where environmental engineers would search for previously neglected characteristics of wastes and for physical, chemical, and biological phenomena that open new opportunities for disposal and reclamation technology.

Implementing such innovations would require greater cooperation between waste producers, resource users, and regulatory agencies than the adversarial relationship that has prevailed so often in the past. Many efforts to protect the environment have been imposed on corporations and some govenment agencies as sources of increased costs, and recently, closer collaboration between regulators and law enforement has increased the rate of prosecution and punishment for violations of environmental regulation (*47*). Changing this spirit of conflict might involve greater efforts not only to develop public markets for recycled wastes (*48*) but also to search for local situations where recycling could be done by private agreements and cooperation between existing organizations.

All of the types of innovation we discuss would have their place in such a development: incremental improvements and new departures, and opportunistic innovations and strategies such as controlled biodegradation. The new orientation of environmental engineering to resource recovery could be a crucial part of a larger scale change of environmental protection efforts, in which activities providing food, shelter, transportation, and related necessities and comforts would seek to accommodate themselves within the environmental limits that we are still struggling to understand.

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