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ROLE OF ANAEROBIC DIGESTION IN ALLEVIATING ENVIRONMENTAL PROBLEMS IN THE UNITED STATES

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The United States has been confronted with an array of environmental problems in recent times. New types of pollutants are permeating groundwater aquifers and the stratosphere threatening air and water quality, the global climate, and the quality of life. Bioprocesses, specifically anaerobic digestion, can play an important role in stabilizing organic wastes, in detoxifying hazardous wastes, in modulating the greenhouse effect of pollutants, and in recovering renewable energy from the pollutant carbon. This paper examines the probable role that anaerobic digestion, in particular, *two-phase anaerobic digestion,* can play to alleviate current environmental problems in the United States.

Key Words : *environmental pollution, hazardous wastes, greenhouse effect, pollution abatement, energy recovery, anaerobic digestion, two-phase*

1. INTRODUCTION

The United States has been confronted with a host of emerging environmental problems during the last 20-25 years. These problems were not clearly foreseen by the public before the first energy crisis and the landing of a man on the Moon in the early 1970s. Americans were not concerned with water and air pollution, and were happy with "safe" (by simple chemical and bacteriological standards of the time) drinking water supplies and good food sanitation practiced by the food-processing industry, supermarkets, caterers, and restaurants. Twenty-five years ago, we were oblivious of *global warming, acid rain, hazardous wastes, groundwater contamination, nonpoint pollution, toxicological effects of chlorinated drinking water,* and other problems that emerged with time as the country entered the age of the microchips. Environmental engineers made tremendous progress during the "space age," so much so that water and wastewater treatment, and even water renovation and reuse by tertiary treatment were taken for granted by American communities. Air-pollution problems in metropolitan areas were alleviated substantially by the application of new unit operations developed to deal with emissions of particulates, carbon monoxide, and nitrogen and sulfur oxides. Successful management of the water- and air-quality problems of the 1950s and 1960s called for celebration. Unfortunately, there was little time for complacency for the American environmental engineer, who then faced a series of *hot* environmental issues that were heretofore ignored, or were subject of curiosity before 1970.

(1) Environmental problem management

In general, it is possible to relate traditional and emerging environmental problems to the municipal, industrial, and agricultural sectors of the economy. A sketch of current environmental issues that have attracted the attention of the American public and the Environmental Engineering Profession is depicted in

Table 1. The importance of these problems is reflected by the enacted legislation.

A review of American legislation enacted in the seventies and eighties clearly indicates that environmental problems of the 21st century need to be *managed* first by nontechnological means. The United States Environmental Protection Agency (USEPA) has been consistently sending a message that says, manage environmental problems first, and apply treatment technologies as a last resort[1]. This is a new idea introduced to traditional engineering approach that normally calls for solving environmental problems by "technological fixes." Management involves the institution of the *born-again,* common-sense strategies of *pollution prevention and waste minimization, cradle-to-grave* tracking and monitoring of raw and treated wastes, materials and energy recovery, application of innovative methods to reduce the volume, quantity, and toxicity of "wastes," and last but not the least, the utilization of waste as a resource.

(2) Technological solutions

Treatment of waste should be the last step in USEPA's waste-management hierarchy simply because current technologies have limited capabilities to cope with hazardous substances and biologically recalcitrant organics. In addition, available waste treatment technologies are often unsuitable for handling such concentrated materials as municipal solid waste (MSW), agricultural wastes, and a number of industrial effluents. Clearly, conventional waste-treatment technologies cannot meet the demands of new environmental legislation. There is a need for new approaches and new systems. To this end, the USEPA and other federal and state agencies have been calling for the development, demonstration and commercialization of *alternative and innovative technologies* to alleviate the impact of the challenging problems listed in Table 1. The purpose of this paper is to examine the role of one important bioprocess technology, *anaerobic digestion,* in tackling some of the environmental problems that we now face.

2. POLLUTION ABATEMENT BY ANAEROBIC DIGESTION

Anaerobic digestion (AD) has been applied in large and small scale for the destruction of organic wastes with simultaneous production of a clean fuel, methane, for about 100 years. Several AD process configurations including *standard and high-rate digestion, anaerobic contact process*, and others are used by consulting engineers. Are these conventional AD technologies effective in adequately meeting the new challenges outlined in **Table 1**? This question and related issues are discussed in the following sections with reference to the usefulness of conventional AD systems in resolving environmental problems of the municipal, industrial, and agricultural sectors of the American economy.

(1)Role of AD in alleviating environmental problems of the municipal sector

Conventional AD process configurations have been applied to stabilize ***dilute*** municipal sludges with total suspended solids (TSS) contents of 1-4 wt% utilizing unduly large, heated, single-stage fermenters ("digestion" tanks) with hydraulic retention times (HRTs) of 14-40 days; higher TSS-content feeds and lower HRTs are not used because in a single-stage fermenter, these operating conditions lead to unbalanced acid and methane fermentations. This imbalance causes volatile fatty acids (VFA) accumulation (*sour digestion*), ensuing pH drops, inhibition of methane fermentation, and ultimately process failure[2]. Even the best available AD technologies (known as *high-rate digestion*) exhibit low volatile solids (VS) conversion efficiencies of about 45% under normal operating conditions. It is due to these serious limitations that conventional AD process designs are not commercially applied in the United States to stabilize high solids-content MSW. Anaerobic digestion has the potential to modulate the adverse environmental impacts of municipal solid waste and sludge, but it is not readily achieved by the current technology.

Ultimate disposal of digested municipal sludge (*biosolids*) has been an intractable problem for many years. Currently, landfill disposal raw of treated biosolids is banned in many American communities, and sludge-composting is increasingly rejected by the public. In view of this crisis, it is imperative first, to double the VS reduction efficiency achievable by current AD technology to minimize the volume and mass of the digested residue, and second, to produce a safe and sanitary end-product from this ubiquitous waste for community use. The USEPA has recently promulgated the so-called *503 regulations* encouraging such *beneficial use* of sludge as land

Table 1. Environmental issues of current concern in the United States

Economic Sector	Current Issues of Concern
Municipal	- Ultimate disposal of biosolids - Solid waste management - Management of high-solid wastes - Greenhouse effect of landfill methane - Recovery of materials and *renewable energy* from waste *resources* - Nutrient removal - Systems for "small flows" - Management of micropollutants - Management of recalcitrants
Industrial	- Water and land pollution by hazardous wastes -Detrimental effects of acid rain on environment and infrastructure - Management of high-strength (high-solids and high-COD) wastes - Pretreatment - Materials and *renewable energy* recovery
Agricultural	- Pollution by pesticides, insecticides, herbicides, nitrates - Nonpoint pollution by organic and hazardous wastes - Management of high-solids and high-COD wastes - Greenhouse effect of agricultural wastes - Materials and *renewable energy* recovery

farming, fertilizer use, and other applications. Processes that effect high pathogen destruction, removal of heavy metals, and degradation of hazardous substances can generate sludge-treatment residues for beneficial use. The conventional AD technologies are not capable of achieving high VS-stabilization and pathogen-destruction efficiencies, nor do they offer any opportunity for the removal of heavy metals. New process configurations are needed to realize the potential utility of anaerobic digestion to mitigate the serious environmentalproblems of our times.

The Resource Conservation and Recovery Act (RCRA) of 1976 encourages the recovery of material and energy resources from MSW[3]. This goal could be achieved by a high-solids anaerobic digestion process exhibiting a high *net-energy production* efficiency. The conventional high-rate digestion process is unsuitable for this purpose, since it fails with concentrated feeds due to the onset of sour digestion, and has a negative or low net energy production efficiency. The potential benefit of anaerobic digestion in recovering energy from MSW is not realized by the conventional AD technology. New AD processes are needed to accomplish this objective.

Biomethanation of MSW and capture of the product methane can help alleviate the greenhouse effect of U. S. landfills, gaseous emissions from which are equivalent in their greenhouse impact to between 2% and 10% of the total U. S. fossil CO_2 emissions[4]. The existing dilute-slurry AD technology cannot be used to this end. An AD system capable of capturing methane from bioconversion of MSW for captive use may significantly alleviate the greenhouse effect of municipal landfills.

(2)Role of AD in alleviating environmental problems of the industrial sector

Solid and liquid industrial wastes contain hazardous and nonhazardous organic materials with high energy values. Anaerobic digestion can be used to catabolize these organic pollutants to reduce toxicity and to recover methane gas from industrial effluents. Indeed, researchers are now reporting that anaerobic systems can destroy a variety of nonchlorinated and chlorinated, aliphatic and aromatic hazardous substances by hydrolysis, cometabolism, reductive dehalogenation, and other biochemical mechanisms. There is ample evidence to indicate that AD can contribute significantly to lessen the threats posed by hazardous wastes.

Several single-stage digestion systems utilizing such fermenter designs as the CSTR (completely stirred-tank reactor), upflow and downflow anaerobic filters, fluidized-bed reactors, biodiscs, hybrid upflow reactors, and the UASB (upflow anaerobic sludge-blanket reactor) has been utilized to treat soluble or low TSS-content industrial effluents. Some of these reactor systems exhibit high substrate conversion efficiencies at relatively short HRTs under special operating conditions and with mostly soluble wastes.

An anaerobic reactor that has been popular commercially is the UASB. This reactor is an improved version of the Dorr *Clarigester;* [5] it operates successfully with carbohydrate- and mineral-rich, low-SS content (<0.5%) wastewaters with COD strengths of less than about 15,000 mg/l. The UASB system relies on biogranules that are formed in the reactor within a reasonable period of time, or are imported from vendors at a high cost and introduced into the system.

Anaerobic filters, fluidized-bed reactors, and biodiscs have limitations similar to those of the UASB in that they cannot be used to stabilize and gasify high TSS- or high COD-content industrial effluents. A large number of industries with significant environmental impact generate high-solids and/or high-COD effluents, which in the environment of a single-stage digester such as those described above, will undergo sour digestion leading to process failure. These AD technologies have limited utility in managing current environmental problems. Innovative multi-stage AD systems capable of separate control of acid and methane fermentations of high-TSS or high-COD wastes and enhanced conversion capabilities are needed to achieve the pollution-abatement and energy-recovery potential of anaerobic digestion.

(3) Role of AD in alleviating environmental problems of the agricultural sector

Agricultural residues and wastes are produced in massive quantities in the United States. These materials contain hazardous substances (see **Table 1**) along with concentrated, highly polluting, odor-causing, nonhazardous organics. The combined effect of these ubiquitous pollutants on the terrestrial and aquatic environment could be devastating in some cases.

The total production rate of agricultural waste including animal manure is about five times that of MSW. Consequently, these waste materials contribute much more to land, stream, and groundwater pollution than municipal or industrial wastes. The greenhouse effect of manure piles and other decomposing materials discarded by the agricultural industry could be more damaging than that of municipal landfills. Admittedly, there is a dearth of information on the effect of dispersed agricultural wastes on terrestrial and aquatic ecosystems.

Anaerobic digestion of agricultural wastes in sealed systems effects carbon and energy recovery at the expense of organic pollutants with simultaneous destruction of hazardous substances and production of a clean biofuel. In theory, it can play a great role in modulating the adverse impact of agricultural pollutants.

There are several technological and economic barriers controlling the application of anaerobic digestion to agricultural wastes. A number of sophisticated system designs were developed and tested in pilot scale at several American universities and by some entrepreneurs. Agricultural wastes contain a high concentration of solids. Some of these materials, for example cheese waste or cheese whey, have highly variable COD concentrations ranging from 30, 000 to 120, 000 mg/l. Conventional single-stage anaerobic digestion is incapable of gasifying and stabilizing these high-TSS or high-COD wastes.

Commercial application of AD to agricultural wastes is mostly restricted to the management of dairy manure in so-called "psychrophilic" plastic-sheet-covered-lagoon digesters, which afford a low methane yield and postpone solids disposal for a future time—frequently less than 10 years—when the lagoon is filled up. Disposal of the accumulated manure from these lagoon digesters have posed serious threats to the environment. The partially digested manure has been regarded "hazardous" by some state and local agencies.

A suitable AD technology can play a decisive role in mitigating nonpoint pollution, and in reducing the greenhouse effect arising from open-air decomposition of the massive amounts of organic material discarded by the agricultural sector of the American economy. An innovative AD technology could go a long way in addressing these seemingly intractable problems since the 100-yr. old single-stage fermentation process cannot mitigate the environmental problems arising from agricultural activities.

3. RENEWABLE ENERGY PRODUCTION BY ANAEROBIC DIGESTION

Anaerobic digestion is effective in recovering renewable organic carbon and solar energy from biomass and wastes in the form of methane. Methane gas can be used as a clean gaseous fuel, or it can be utilized to generate electric power via *gensets* or fuel cells. A digestion process configuration that is used for energy production must necessarily maximize organics conversion as well as net energy production. It must be capable of processing high-solids and high-COD wastes to minimize the energy required to heat the water fraction in the digester feed slurry. The process must also utilize the smallest possible reactor to minimize surface heat loss, and to reduce capital cost. In addition, the process design should rely on mixing by indigenous gas production as much as possible to minimize the input of external mixing power. Conventional high-rate digestion has a poor record in all these areas. Improved AD technologies that incorporate the above design features are needed for efficient renewable energy production from biomass and wastes.

4. IMPACT OF ANAEROBIC DIGESTION ON ENVIRONMENTAL QUALITY

(1) Present situation

Available anaerobic digestion process designs handle dilute organic wastes, convert about 40% of the organic feed, and produce little or no net energy. The reliability of the conventional process configurations has been questioned. Even the best process design (high-rate anaerobic digestion) is fraught with severe operating problems. Thus, anaerobic digestion, as it is practiced now, was developed decades ago to meet limited objectives; it cannot be expected to meet new challenges and to be effective in addressing the current environmental issues (see **Table 1**). A lack of enthusiasm on the part of policy makers to rely on AD for environmental-quality control seems to support this view

(2) Future potential

As discussed in the foregoing sections, an *efficient and appropriate* AD technology can be an effective tool for improving the quality of the total environment. Efficient and rapid-rate gasification of municipal biosolids, MSW, industrial effluents, and agricultural wastes with simultaneous destruction of hazardous waste constituents could combine pollution abatement with generation of renewable energy to displace fossil fuels. An appropriate AD technology can significantly alleviate the greenhouse effect of municipal landfills and depositions of industrial and agricultural wastes. Such a technology needs to be developed, tested, and applied. This is the challenge environmental engineers now face.

5. PROCESS DEVELOPMENT NEEDS

An AD technology that plays a decisive role in alleviating land and water pollution, and in reducing the greenhouse effects of decomposing organic wastes must, at a minimum, satisfy the following requirements:

- Convert high-solids and high-COD feeds efficiently in stable fermenters
- Exhibit VS conversion efficiencies higher than 75% or COD conversion efficiencies higher than 85%
- Afford a high net energy production efficiency
- Withstand digester operation at short HRTs and high loading rates
- Ensure fast startup, and reliable and resilient operation
- Developed and proven by laboratory, and pilot- and full-scale operation with real pollutants
- Eliminate/alleviate common operating problems (e.g., foaming, corrosion).

6. DEVELOPMENT AND APPLICATION OF TWO-PHASE DIGESTION

Table 2 Environmental conditions and endproducts of phase-separated anaerobic digestion

Phase I Digester ("Acid Phase")		Phase II Digester ("Methane Phase")	
Environment	Endproducts	Environment	Endproducts
Acidic (pH: 4.5-5.5) ORP: - 200 to 250 mV	VFA (5-15 g/l) CO_2 (60-75%) CH_4 (25-40%) N_2 (1-4%) $S^=$ (up to 1000 ppm)	Alkaline (pH: 7.4-7.8) ORP: - 380 to - 450 mV	VFA (< 0.5 g/l) CO_2 (32-15%) CH_4 (68-85%) N_2 (0-1%) $S^=$ (trace)
Dilution Rate: High (1-3/day)		Dilution Rate: Low (0.1-0.3/day)	

This writer has devoted 25 years in a continuing endeavor to develop an innovative approach to AD system design to meet a majority of the above requirements. As described in several publications and patents, this innovative and unconventional AD technology, known as *two-phase anaerobic digestion (TPAD),* rely on separate optimization of the major fermentation phases, and conducting the overall digestion process in two biodigesters operated in series.[6) ~ 9)] The physical-chemical environment in the first fermenter (Phase-I digester) is manipulated by *kinetic and loading-rate control* to enrich the fast-growing, hydrolytic acid-forming bacteria, sulfate reducers, and denitrifiers. Slow-growing acetate-formers (acetogens) and aceticlastic methanogenic bacteria are enriched in the second fermenter (Phase-II digester) by kinetic control as well as by regulated feeding of VFA substrates from Phase-I fermentation. Environmental conditions in Phase-II digester are optimized to maximize methane production. Acid-base and redox environments in each digester can be manipulated by inter- and intra-fermenter recycling of digester effluents. **Table 2** summarizes the environmental conditions and end-products of separated fermentation phases.

The TPAD technology was first proven in the late 1970s by pilot- and full-scale application to soluble industrial wastes in collaboration with European users[10)]. Feasibility of commercial application of the process to solid substrates was demonstrated in the United States in the late nineties.

(1) Pollution abatement and energy recovery by "high-solids" digestion

A full-scale two-phase anaerobic digestion process, known as the Acimet® Process, was installed in the United States for gasification and stabilization of high-solids municipal sludge. This program was undertaken with support from the State of Illinois and the County of DuPage to accomplish three major objectives:

1. Maximize VS reduction, and gas and methane production from bioconversion of concentrated municipal biosolids
2. Maximize organic and hydraulic loading rates
3. Alleviate or eliminate foaming attributed to the presence of *Nocardia* species in the raw waste activated sludge—a chronic operating problem prevalent in more than 60% of U. S. digestion plants.

Design of the full-scale plant, which replaced an existing high-rate digestion system, was based on operating experience with a large-scale pilot plant at DuPage County[11) ~ 13)]. As shown in **Table 3**, solids concentration of the two-phase system feed was double that of the high-rate system feed. Higher solid concentration could be used for two-phase digestion, but pumping sludge with TSS concentration higher than 9 wt% is not readily achieved by conventional sludge pumps.

The commercial-scale TPAD system consisted of a 6.4-m dia. X 10.3-m deep acid-phase digester operated in tandem with a 16.6-m dia.x 8.5-m deep methane-phase digester. (An existing high-rate digestion tank, the capacity of which was 200% that of the required methane-phase digester, was utilized to reduce plant capital cost thus resulting in an oversized system.)[12),13)] Both digesters were operated in an upflow mode at a mesophilic (37°F) temperature. There was no mechanical or compressed-gas mixing of the digester contents. Full-scale performance data presented in **Table 3** show a high gas yield of about 80% of the theoretical value, which was consistent with a high VS reduction of up to 80%.

Table 3 Comparison of performances of two-phase and high-rate anaerobic digestion of municipal sludge at DuPage County, Illinois, U. S. A.

Parameter	Conventional High Rate	Two phase
Feed TS, wt%	3.0 - 5.0	7.5 - 9.0
Loading rate, kg VS/m^3-day	0.4 - 2.0	2.6 - 4.7
HRT, day	14 - 40	10 - 14
pH	6.7 - 7.2	7.5 - 7.7
Alkalinity, ppm $CaCO_3$	4000 - 6500	7000 - 7500
Gas yield*, SCM/kg VS added	0.29 - 0.48	0.66 - 0.85 (80% of theoret.)
Methane, mol %	58 - 62	63 - 67
VS reduction, %	16 - 45	69 - 80
Effluent VFA, mg/l	460 - 1400	170 - 300
Net energy, 10^6 kcal/day	4.76	18.04 (3.8 x high rate)
Pathogen reduction	Class B sludge	Class A sludge
Nocardia foaming	Severe	None

*Theoretical gas yield = 1.06 SCM/ kg VS added

Two-phase fermentation doubled the gasification and pollutant-destruction efficiencies achieved by old high-rate digestion. Enhanced gas production and reduced operating energy by virtue of high-solids content of the feed and elimination of mixing with external power had the desired effect of increasing net energy production (NEP). Average NEP of the two-phase process is about 3.8 times that of old high-rate digestion. Other important advantages of the two-phase process include the following:

- Elimination of digester foaming owing to enhanced hydrolysis of the *Nocardial biomass*
- Increased process resilience as demonstrated by quick digester recovery from temperature and loading shocks
- Containment of sulfide generation in the acid digester resulting in the production of "a sweeter" methane-digester gas
- Maintenance of a high methane-digester alkalinity of about 7500 mg/l to ensure process stability.

(2) Pollution abatement and energy recovery from high-COD wastes

In the United States, the environmental impact of agricultural activities could be higher than that of other economic sectors as measured in terms of soil and water pollution, and uncontrolled release of greenhouse gases from landfarming and piling of agricultural wastes. Animal manure and dairy-industry effluents together constitute one of the major threats to the environment. Fortunately, with proper management and application of appropriate technology, these high-solids and high-COD wastes could also be beneficial to the economy as they represent a reservoir of renewable energy. It has been estimated that the energy value of agricultural food residue, dairy-industry wastes, and animal manure is equivalent to 12% of the national energy demand. To cite one other attractive statistic, methane produced from cheese-factory wastes can meet 45% of the plant energy demand. It is obvious that great environmental and economic benefits can be derived by efficient biogasification of these potent pollutants.

Agricultural wastes are generally dispersed. However, a favorable situation exists in America's dairylands where wastes from confined barns, cheese factories, ice cream making, and other manufacturing activities can be collected in an organized fashion. The collected mixed waste can be processed in a centrally located conversion plant. Since these organic wastes have high moisture contents and are heterogeneous in nature, anaerobic digestion seems to be the ideal process for simultaneous stabilization and energy conversion. However, conventional high-rate digestion is unsuitable for these wastes having varying COD concentration of 20, 000 to 125, 000 mg/l—waste strength varies weekly and by season—and high TS concentrations. This situation offered an opportunity to apply a new approach, such as two-phase digestion, the utility of which was already proven by its commercial application to industrial effluents and municipal sludge.

A two-phase pilot plant was installed in Wellsville, Utah—Wellsville is located in Utah's dairyland—with support from the U. S. Department of Energy, the State of Utah, and WesTech Engineering, Inc. to test

Table 4 Biomethanation of mixed dairy-industry wastes

Conditions:
Total COD: 45, 000 - 60, 000 mg/l (coeff. of variation = 5.6 %)
Final effluent recycling to Phase-I digester: 10 % of plant flow
COD reduction: ≈ 97%.

Digester/System	HRT (days)	pH	VFA (mg/l)	CH_4 (mol%)
Acid-phase	2.7	5.6	5930	26
Methane-phase	16.0	7.3	0	73

Table 5. Biomethanation of Mixed Dairy-Industry Wastes

Conditions:
Total COD: 27, 000 - 79, 000 mg/l (coeff. of variation = 14.7 %)
Final effluent recycling to Phase-I digester: 10 % of plant flow
COD reduction: ≈ 73 - 82 %.

Digester/System	HRT (days)	pH	VFA (mg/l)	CH_4 (mol%)
Acid-phase	2.5	5.7	5550	40
Methane-phase	14.8	7.4	1650	78

the technical feasibility of bioconversion of mixed dairy-industry wastes.[14] The pilot plant had a capacity to process about 6% of a cheese plant's waste. Thus, a full-scale plant is obtained by scaling up the pilot plant by a factor of 16. Results of pilot plant operation with real wastes collected from a local cheese plant and a dairy farm showed that a high mesophilic (32°C) methane yield of 0.3 to 0.4 m^3/kg COD added can be obtained by the two-phase process with COD reductions up to 97% (**Tables 4** and **5**). The COD reduction efficiency declined with higher COD concentrations and higher COD variability, as expected (**Table 5**). However, this efficiency decrease can be avoided with a raw-waste equalization tank that was not part of the pilot plant, but is essential for a full-scale system. The methane digester gases had a high methane content of 73 - 78 mol%.

An examination of acid- and methane-digester response in terms of pH, VFA generation, and methane concentration shows the high stability in system performance even in the face extreme variation in waste strength. It should be noted that residue from two-phase digestion has a high nutrient value. It is at least as marketable as the bagged cow manure now sold at attractive prices in America's garden stores.

The TPAD system design tested at Wellsville, Utah represents a good start towards the development of a modern agricultural management system that is expected to be effective in modulating the adverse environmental effects of massive quantities of agricultural wastes.

7. SUMMARY AND CONCLUSIONS

The United States, and other developed and developing countries are confronted with a host of environmental problems threatening water and air quality, the global climate, and the quality of life. Besides conventional pollutants, we now have thousands of man-made hazardous substances that have pervaded the terrestrial and subterranean environment. These substances have permeated into groundwaters, which form the life blood of hundreds of communities in every country. Some of these pollutants seem indestructible, and cause morbidity and terminal illness upon prolonged ingestion of and exposure to these substances in microconcentrations. Conventional technological fixes often fail to correct these problems. Such born-again management strategies as pollution prevention and waste reduction may be the most important methods of pollution control of the future.

By nature, the pollutant load is heterogeneous in nature; it remains in association with high quantities of moisture. For this reason, biological attack is often the most economical and practical means of converting pollutants to innocuous substances. Bioprocess, such anaerobic digestion, could provide the appropriate means of accomplishing this goal, since it is not limited by the requirement that oxygen be supplied at all times. Anaerobic digestion has been used for 100 years for the stabilization of municipal wastes. Unfortunately, the conventional digestion process design developed to solve simple problems of yesteryears can hardly meet today's challenge. It is inefficient and outdated. It is not effective for high-strength wastes.

Anaerobic digestion is a complex fermentation system. It can play an important role in alleviating air, land, and water pollution problems and the potential greenhouse effect of municipal, industrial, and agricultural wastes; it can detoxify hazardous wastes. New fermentation system designs are needed to ensure a proper role for anaerobic digestion in the global struggle for environmental restoration. One system design that can help the cause of anaerobic digestion in this respect is two-phase anaerobic digestion, which has been in commercial practice since the late 1970s. Full-scale operating experience with high-solids and high-COD waste streams shows that this process is capable of doubling the VS-reduction efficiency and quadrupling the net-energy production efficiency of conventional high-rate digestion. The TPAD process needs further refinement, testing, and modification to assume an appropriate role in the management of global environment for a better life.

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米国における環境問題解決のための嫌気性消化法の役割

サム　ゴーシュ

近年，アメリカは深刻な環境問題に直面している．新しいタイプの汚染物質は地下水圏そして大気圏へと浸透しており，水や空気の汚染が進むことで世界規模の気象や日常生活が脅かされ始めている．生物学的プロセス，特に嫌気性消化法は有機性排水の安定化に対して，有毒排水の無害化・地球温暖化の調整・汚染物質からのエネルギー回収等の重要な役割を担っている．ここでは、アメリカにおける現在の環境問題の解決に対して嫌気性消化法の中で特に二相嫌気性消化法が果たすべき役割について検討を行った．