Anaerobic digestion for sustainable development: a natural approach

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Abstract After the discovery of methane gas by Alessandro Volta in 1776, it took about 100 years before anaerobic processes for the treatment of wastewater and sludges were introduced. The development of high rate anaerobic digesters for the treatment of sewage and industrial wastewater took until the nineteen-seventies and for solid waste even till the nineteen-eighties. All digesters have in common that they apply natural anaerobic consortia of microorganisms for degradation and transformation processes. In view of this, it could be rewarding to evaluate the efficiency of natural ecosystems for their possible application. Examples of high rate anaerobic natural systems include the forestomach of ruminants and the hindgut of certain insects, such as termites and cockroaches. These “natural reactors” exhibit volumetric methane production rates as high as 35 l/l.d. The development of anaerobic reactors based on such natural anaerobic systems could produce eco-technologies for the effective management of a wide variety of solid wastes and industrial wastewater. Important limitations of anaerobic treatment of domestic sewage relate to the absence of nutrient and pathogen removal. A combination of anaerobic pre-treatment followed by photosynthetic post-treatment is proposed for the effective recovery of energy and nutrients from sewage. This eco-technology approach is based on the recognition that the main nutrient assimilating capacity is housed in photosynthetic plants. The proposed anaerobic-photosynthetic process is energy efficient, cost effective and applicable under a wide variety of rural and urban conditions. In conclusion: a natural systems approach towards waste management could generate affordable eco-technologies for effective treatment and resource recovery.

Keywords Anaerobic digestion; anaerobic-photosynthetic treatment; natural systems; nitrogen cycle; nutrient recovery; sewage treatment; stabilisation ponds

Anaerobic digestion in an evolutionary perspective

The environment in which we live has to a large extent been determined by the activities of a wide range of different organisms, which interact with each other and with their immediate environment. Human activities are of major importance in this respect. Until about 250 years ago humanity existed in relatively small numbers, while the environmental impact per person was low. The impact of human activities on the state of the environment on a global scale therefore was limited. The explosive growth of population and of industrialisation during the past 200 years, however, has been accompanied by serious environmental pollution, both locally and on a global scale. We live in a human dominated planet, where drastic changes in the environment are triggered by human action in an uncontrolled way. Changes in the environment, however, are not new. The earth has been subject to changes right from its early existence about 4.6 billion years ago. When the first forms of life appeared on earth some 3.7 billion years ago, the entire environment was anaerobic. The atmosphere constituted a reducing environment with substantial amounts of CH₄, CO, CO₂, HCN, H₂, N₂, and NH₃. The anaerobic environment was maintained until about 2.3 billion years ago, when oxygen production was started by cyanobacteria. The appearance of photosynthesis generated an “explosion” of biomass production and the activity of the increased photosynthetic biomass eventually resulted in the present level of 20% oxygen in the atmosphere. The significant increase in biomass also brought drastic changes to the origin of methane production. Inorganic compounds formed the main sources before
the existence of photosynthesis, but now the main source of global methane production is acetate and hydrogen derived from anaerobic degradation of biomass.

While the overall environment gradually became more aerobic, anaerobic microorganisms continued to grow in anaerobic niches, such as marshes, sediments, wetlands, and in the digestive tract of ruminants and certain species of insects. Current global methane emissions from these natural sources are estimated to amount to 295 to 570 million tons of methane per year (Zinder, 1993). The current atmospheric concentration of methane is estimated at about 1.6 ppm, which accounts for about 15–20% of the overall greenhouse effect. In view of the fact that anaerobic digestion is a natural process that has existed already for several billions of years, it could be rewarding to intensify studies on the microbial ecology and physiology of natural anaerobic consortia. The knowledge acquired in this way could prove to be useful for further improvement of anaerobic digestion technologies.

**Anaerobic digestion in a historical perspective**

After the discovery of methane emissions from natural anaerobic habitats by Volta in 1776 (Barker, 1956), some people started collecting the natural biogas and used it as a fuel, basically for lighting. It took until the end of the 19th century until anaerobic digestion was applied for the treatment of wastewater and solid waste. Since anaerobic digestion is a multi-step process, which involves the successive action of metabolically diverse populations of microorganisms, the overall rate of conversion of organic matter is governed by the kinetic characteristics of the slowest step. Technology development for the anaerobic treatment of solid waste and of wastewater followed different paths, because of differences in the rate limiting step (Figure 1). While hydrolysis of cellulose and other polymers proved to be the rate limiting step for solid waste (Noike et al., 1985; Op den Camp and Gijzen, 1991), acetogenesis and methanogenesis appeared to be rate limiting in case of wastewater treatment (Gosh and Pohland, 1974).

**Anaerobic digestion of solid wastes**

The Chinese-type or fixed dome reactor and the Indian-type or floating drum reactor have been applied for a long time in rural Asia and more recently also in Africa, with the main purpose to recover energy from manure and agricultural wastes. Both reactor types are cheap in construction and simple in operation, but volumetric gas production rates are low due to the long retention time of the waste materials in combination with low conversion efficiency. The application of anaerobic digestion with the main purpose to reduce and stabilise solid waste became popular after the large-scale introduction of activated sludge systems some 50 years ago. Anaerobic sludge digestion is still standard practice for modern activated sludge plants.

The development of high rate anaerobic digestion technology for solid waste was delayed till the 1980s and 1990s and important developments are still in progress. High rate digestion requires high hydrolytic activities in the reactors, while a balance must be maintained between acidogenic and methanogenic reactions to prevent acidification. Recent efforts have been aimed at developing dry anaerobic digestion, which allows high volumetric loading of reactors. One of the successful developments includes the Dry Anaerobic Composting (DRANCO) process (de Baere and Verstraete, 1984; de Baere, 1999). The system has been applied to treat different types of waste, including market waste, municipal solid waste and sludges. Several full-scale plants have been constructed in Europe and in Asia. Other high rate systems for anaerobic digestion of solid organic wastes are marketed under the names Valorga, Biocel and Vagron.
Anaerobic wastewater treatment

The first application of anaerobic digestion for sewage treatment dates back to about 1860, with the development of a simple air-tight chamber by Mouras in France (McCarty, 2001). In 1897 the local government board of the city of Exeter, England, approved the treatment of the entire wastewater of the city in a similar anaerobic system, referred to as septic tank. At the beginning of the 20th century Imhoff developed a slightly more advanced digester which combined sedimentation and digestion in a single compartment. Primitive anaerobic filters and hybrid systems were also introduced around the turn of the century (McCarty, 2001). These early digesters were not heated and no mechanical mixing was applied. Although anaerobic wastewater treatment has been used since the late 19th century, it has for a long time been considered to be an unstable, inefficient and slow process. A major limitation in the development of high-rate anaerobic digesters has been the low yield and long doubling times of the microorganisms, especially for those involved in the acetogenic and methanogenic reactions. Due to a rapid escalation of energy costs and increased environmental awareness in the 1970s, anaerobic treatment gained more attention in terms of research and technology development. This resulted in a better understanding of the complex microbial processes and in a number of improvements of the technology. The successful retention of biomass in the reactor via immobilisation or granulation appeared to be the key to developing high-rate systems. The different designs of retained biomass reactors developed over the past 30 years include the anaerobic filter (Young and McCarty, 1967), the upflow anaerobic sludge blanket (Lettinga et al., 1980), the fluidised and expanded bed reactors (Switzenbaum and Jewell, 1980), and the down-flow stationary fixed film reactor (Murray and van den Berg, 1981). Many discussions have been dedicated to the choice between aerobic or anaerobic systems for wastewater treatment. Developments over the past 15 years have demonstrated that the anaerobic process may be an attractive and viable alternative for the treatment of a wide range of industrial wastewaters. To date many applications of anaerobic treatment of industrial wastewater exist, while the application to domestic wastewater has been demonstrated for (semi) tropical regions (van Haandel and Lettinga, 1994).

Anaerobic digestion – a natural approach

All anaerobic digesters have in common that they apply natural anaerobic consortia of microorganisms for the transformation and degradation processes. Further studies on natural anaerobic ecosystems could provide valuable knowledge, for further technology improvements. The breakthrough in anaerobic wastewater treatment was made by the “discovery” of immobilisation, a concept that is commonly observed in natural ecosystems. Considering the rate-limiting step for the anaerobic digestion of solid organic matter, it

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**Figure 1** Anaerobic digestion in a historical perspective
would make sense to evaluate natural anaerobic systems for their hydrolytic activity. Cellulose is the most abundant biopolymer on earth, but the number of species that produce cellulase activity is very low. With only few exceptions, cellulase is a microbial enzyme, which is produced only by very few specialised species. Some natural anaerobic systems appear to be extremely efficient in cellulose conversion. Examples of such systems include the rumen of cattle and the hindgut of insects (Gijzen et al., 1986; Gijzen et al., 1991; Gijzen and Barugahare, 1992). The digestion processes in these systems are entirely catalysed by microorganisms and combine the action of a diverse population of anaerobic bacteria, protozoa and fungi. The “Rumen Derived Anaerobic Digestion” (RUDAD) system is a concept developed at the University of Nijmegen and is basically a copy of the rumen microbial system (Gijzen, 1987). The efficient hydrolytic activity of the rumen reactor is coupled to a high-rate anaerobic wastewater treatment plant for conversion of the generated organic acids into biogas. Laboratory and pilot trials showed that a wide variety of bio-wastes could be digested at organic loading rates of up to 40 kg/m³.d. The practical application of the RUDAD system has not been successful yet, because of technical limitations in separating solids and liquid flows, which pass the system at different rates.

Besides ruminants, termites and cockroaches also produce large amounts of methane. The production of methane from insects has been recognised as an important source of global methane production and as such contributes to the greenhouse-gas effect. Measurements of methane emissions from the cockroach Periplaneta americana revealed that volumetric productions were even higher than from the rumen microbial system (Gijzen and Barugahare, 1992). With a volumetric methane production of 35 ml/ml.d, the cockroach hindgut appears substantially more efficient than any anaerobic reactor currently available. Since methane is just a by-product of hindgut fermentation, the potential production of biogas could be much higher if the acetic acid produced could also be further converted to methane. The development of an anaerobic reactor based on the microbial processes of the cockroach hindgut would make sense.

The examples above show that natural anaerobic ecosystems hold great promise for high rate anaerobic waste management; the exploitation of such microbial systems, in order to develop effective eco-technologies, calls for closer interactions between microbial ecology and biotechnology disciplines.

Sewage management – a natural approach

Cost of sewage management

Over the past decades we have seen various programmes, which aimed to achieve full coverage of water supply and sanitation services world-wide. The aim of water supply and sanitation for all could not be achieved during the water decade (1980–1990), nor was it possible to satisfy this objective by 31 December 2000 as defined under the Safe Water 2000 programme. Vision21, the water supply and sanitation paragraph of the recently formulated World Water Vision has again defined a target to achieve full coverage of these services (Cosgrove and Rijsberman, 2000). This time the target date is the year 2025. According to WHO data, this means that daily 310,000 people will need to receive improved water supply and about 460,000 improved sanitation (WHO, 2000). Whether this will be achieved this time will largely depend on political commitment, creativeness of sector organisations and the ability to mobilise the required annual investment of 75 billion US$. An immediate consequence of any success on the water supply front is that the volume of sewage produced will proportionally increase. Today sewage presents the main point source water pollutant on a global scale. For most countries in developing regions only a small fraction of the sewage produced receives any treatment. This is because, current mainstream technologies, such as the activated sludge process with N and P
removal, are too costly to provide a satisfactory solution for the growing wastewater problems in developing regions (Grau, 1994; Gijzen and Ikramullah, 2001). This is also illustrated in Figure 2, which demonstrates that the actual unit costs for wastewater treatment infrastructure are generally higher than those of urban water supply infrastructure. Gunnerson and French (1996) demonstrated that the ratio disposal/supply costs increases substantially when service levels and water consumption increase. In this respect a waste minimisation approach, aimed at reducing water consumption could yield substantial savings, at both the supply end and on the sanitation end of the pipe (Gijzen, 2001).

Willingness to pay for water supply services (a product) is generally higher than for sanitation (waste) infrastructure. This fact, together with the higher costs per unit of volume underscores the complexity of sewage collection and treatment world-wide. The success of Vision21 for developing regions to a large extend depends on the ability to develop effective, rational and affordable treatment strategies for sewage.

Rationale of current concepts

Technology choice. Although anaerobic systems were introduced in the 19th century, currently the activated sludge process is the most widely used technology for sewage treatment. With the development of high-rate anaerobic reactors for wastewater treatment, the anaerobic route has gained renewed interest. Due to significant reductions of degradation rates at low temperatures, high-rate anaerobic sewage treatment is only practised in (semi-) tropical countries so far. The generation of biogas from dilute domestic sewage, however, is not attractive and until now none of the anaerobic systems constructed for sewage apply commercial exploitation of the generated gas. Substantial reductions in domestic water consumption could produce more concentrated sewage, which could make energy recovery attractive. Exploitation of generated biogas is important, because it positively affects the overall energy balance of the process and replaces an equivalent amount of non-renewable energy and greenhouse gas emissions. This contrasts favourably to the high external energy requirements for activated sludge operation.
Treatment objectives. Traditionally sewage treatment has been concerned with the removal of BOD and SS, but more recently legislation is becoming more strict with respect to N and P levels in the final effluents. The European Urban Wastewater Treatment Directive demands effluent (total-)N and P concentrations below 10 and 1 mg/l, respectively, by 2005 (European Environment Agency, 1998). This makes sense if we consider the fate of N and P from wastewater if no reductions were to be achieved. An average concentration of 50 mg/l of total-N in sewage may lead to the production of almost 1,000 mg/l (dry wt) aquatic plants or algal biomass. Besides numerous direct negative effects of eutrophication, the generated biomass will turn into BOD at the end of its life cycle. The amount is equivalent to about five times the original BOD present in sewage and therefore it seems questionable whether BOD should remain a priority treatment parameter over N and P.

Modern activated sludge plants for sewage treatment apply tertiary treatment for the removal of N and P via biological processes. This has been realised by configurations, where sewage is exposed to anaerobic, anoxic and aerobic conditions in different parts of the treatment plant (Henze et al., 1995). In this way optimal conditions with respect to absence or presence of BOD and oxygen are created for effective biological N (BNR) and P removal (BPR). Due to the high costs of advanced activated sludge systems, we estimate that probably less than 3% of all sewage produced world-wide currently receives tertiary treatment. It is clear therefore that most of the N and P released via sewage discharges reaches fresh water resources and causes widespread eutrophication (Gijzen and Mulder, 2001). During the anaerobic treatment of sewage, nutrients are mineralised to ammonia and phosphate, but not removed. The effluent of anaerobic sewage treatment plants therefore requires post-treatment in trickling filters, activated sludge systems or stabilisation ponds to achieve nutrient removal. Stabilisation ponds have the added advantage that pathogens are also effectively removed, which provides possibilities for re-use of the effluent.

Anthropogenic versus natural cycle of nitrogen. If we look at BNR in the context of the overall food production and consumption cycle, the current practice does not seem rational. The production of chemical nitrogen fertiliser via the Haber–Bosch process, about $9 \times 10^{10}$ kg in the year 2000, is possible at the expense of vast quantities of non-renewable energy. After consumption of the resulting protein crops grown via fertiliser application, nitrogen is released again in the form of domestic sewage and animal manure. When applying the BNR process to sewage, potentially useful reactive forms of nitrogen are recirculated to atmospheric N$_2$. This process again proceeds at the expense of energy input, and therefore this approach appears inefficient in terms of resource utilisation. Comparison of the anthropogenic N-cycle with the cycle as it occurs in nature reveals some important differences. In contrast to the “wasteful” approach of the anthropogenic cycle, the re-use of mineralised nutrients is a common principle of biological systems in nature. Nitrogen fixation in nature is catalysed by few species of specialised bacteria (e.g. Rhizobium). After fixation nitrogen is subject to a series of conversion steps to form microbial, plant and animal protein, which eventually ends up as dead organic biomass. Upon mineralisation of this dead biomass in soil and sediments a major portion of the produced inorganic N-compounds (a.o. nitrate, ammonia) is assimilated again by plant or microbial biomass for primary production. Only a tiny fraction of these reactive inorganic N-compounds will leave the biosphere via denitrification. This means that in nature a shorter cycle (direct re-use in primary production) is preferred over the long cycle, which runs via N$_2$. This strategy contributes to a higher energy efficiency in biological systems.
A natural approach

Unlike the linear “production-consumption-waste” approach adopted by human society, natural cycles do not tend to accumulate “waste” over ecosystem time scales. A recycling approach, similar to the situation in nature could also be adopted for the anthropogenic N-cycle. This means that the management of animal manure and domestic sewage should be geared towards the effective re-use of nutrients by photosynthetic organisms such as algae, aquatic macrophytes, wetland vegetation or agricultural crops. This could be achieved via direct irrigation with treated effluents that meet WHO guidelines, or via the selective recovery of N and P at source or from the waste stream. An example of the latter is the possible separation of urine at source, followed by centralised recovery of N and P fertiliser (Larsen and Gujer, 1996). Another example is the possible combination of anaerobic sewage treatment followed by photosynthetic post-treatment in stabilisation ponds (Gijzen 2001). Conventional stabilisation ponds for sewage treatment apply this principle, but the algal biomass cannot be easily harvested and consequently nutrients are released again upon degradation of the algae in the maturation pond. The use of dense cover of selected aquatic macrophytes, such as duckweed, might be more effective for nutrient recovery. By selecting optimal applications of the plant biomass and pond effluent, nutrients could end up as high quality fish and crop protein. The combination of duckweed-based sewage treatment and aquaculture is being practised at a small scale (3,500 capita) by an NGO in Bangladesh (Gijzen and Ikramullah, 1999). Every day, about 20% of the duckweed cover is harvested from the stabilisation ponds and fed directly to adjacent fish ponds. The fish produced consists of a polyculture of various species of carps and tilapia. The results over the past years of continuous operation have shown that this combined wastewater–aquaculture system produces over 12 tons fish per ha/y, yielding a net annual profit of about US$ 2,000 per ha. The resource recovery performance of this scheme could be further improved by replacing the anaerobic pond with a high rate anaerobic reactor. The financial performance could be improved by arranging a multi-functional use of available land area via a combination of wastewater treatment, aquaculture, (effluent) irrigated agriculture, and recreation. With the income from the products generated (i.e. energy, irrigation water, crops, fish, recreation facilities), the proposed integrated system has the potential to be operated as a viable enterprise generating substantial revenues from waste management. The large-scale application of such recycling approaches will only be possible in a staged approach. It requires substantial changes in the current water supply and sewerage infrastructure, with the aim to minimise wastewater production and to apply source separation to prevent the build up of toxic chemicals in the food chain.

Conclusions

• Anaerobic digestion is a natural process, which occurs in habitats where oxygen, nitrate and sulphate levels are low and organic matter is present. These habitats account for an annual methane production of about 295 to 570 million tons per year. In view of the fact that some specialised natural systems, such as the rumen of cattle and the hindgut of certain insects, exhibit very high methane production rates it is recommended to study such systems for application in anaerobic waste management. Considering their evolutionary success and the millions of years of experience, such systems can be regarded as proven “eco-technologies”.

• Sewage is the main point-source pollutant on a global scale. Current mainstream technologies for wastewater treatment, such as activated sludge and tertiary nutrient removal, are too costly to provide a satisfactory solution for the increasing wastewater problems in developing regions. Besides, these technologies do not allow for re-use of valuable energy and nutrients contained in the wastewater. The natural capacity
for nutrient recovery is harboured in plants. Therefore, a combination of anaerobic pre-treatment followed by macrophyte-covered stabilisation ponds is proposed for the effective recovery of energy and nutrients from sewage.

- The development of effective and feasible concepts for sewage management provides a huge challenge for the coming decades, especially for low-income regions. Wastewater management should be considered within the wider context of sustainable development. This means that a holistic approach must be followed, where the management of wastewater is linked to that of water resources and of nutrients.

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