

Chapter 1

The Route of Anaerobic Waste (Water) Treatment toward Global Acceptance

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Although the feasibility of anaerobic wastewater treatment (AnWT) has been successfully demonstrated over 100 years ago, its development and implementation had been hampered for decades until the re-introduction of the anaerobic filter process in the 1960s and the technological breakthrough in the 1970s of the upflow anaerobic sludge blanket (UASB) process. This has led to the further developments of a number of modern high-rate AnWT systems, such as expanded granular sludge bed (EGSB) reactor, and anaerobic baffled reactor (ABR), for numerous types of industrial wastewaters. Furthermore, UASB reactor systems have been successfully applied for the treatment of raw domestic sewage, followed by an aerobic polishing post-treatment, if needed; the enormous potentials of the innovative micro-aerobic post-treatment will soon be demonstrated at full scale. Moreover, based on improved understanding of these processes, e.g., in the microbiology, biochemistry, the immobilization of required organisms and consortia, and reactor and process technology, and in control and steering, undoubtedly substantial further progress in the applicability of these anaerobic systems will be achieved in near future. These treatment systems, greatly based on the Natural Biological Mineralization route (NBM), are going to act as a crowbar to force Environmental Protection toward a significantly more sustainable tackle. They enable closing of water and substance loops, viz. valorization of pollutants, reuse of treated water, and will stimulate minimization of wasting of clean water in wastewater collection and transport. Along with the implementation of these systems a major step will be made toward more sustainability in society.

1. Introduction

Consciousness of the humanity, including that of environmental protection (EP), is growing in all domains of society. The question is, however, whether or not it grows fast enough, regarding the exponential developments in science and technology. Is mankind becoming sufficiently capable to employ its enormous scientific, technological, and cultural achievements optimally for the well-being of future citizens, all of them, and wherever living? In essence, and in line with the ideas of the Brundtland Commission (1987), it is in that way how the notion sustainability should be interpreted with three main pillars, namely:

- socialization of human society, i.e., maximization of social security for all world citizens,
- resource conservation, both fossil and living, and
- optimizing development of humanity, with emphasis on education and talent development.

It is the moral task for individual humans to contribute to these issues. The question is whether they are capable, becoming sufficiently aware in time about the “whys and hows”. During their short lifetime, consciousness of individual humans develops somewhat similarly to mankind over millions of years, urging them to contribute. Are we controlling or just following the process of social consciousness? Regarding the exponential developments in science and technology, but at the same time comparably slow progress made in public awareness of all the three sustainability pillars, we face risks for dangerous unbalances in society. Science and technology should always remain well rooted in human society, i.e., not become self-controlling, leading to a disastrous robotization.

Back-casting how things in various sectors in society developed, for instance, in the domain of public sanitation (PuSan) and environmental protection (EP), it is clear that many decisions made in the past were far from optimal, neither for society as a whole nor for separate communities. Illustrative is how things evolved with respect to the development and implementation of anaerobic digestion (AnDi) and anaerobic wastewater treatment (AnWT) systems. Why is that AnDi and AnWT didn't get the core-position in wastewater, why is that so much emphasis in the thirties has been put on the development and implementation of the aerobic wastewater treatment (AeWT) concept, why is that the implementation of modern AnWT proceeded so much smoother in the industrial sector than in the PuSan sector, why is that so much emphasis has been put on extremely centralized off-site sanitation concepts and so tiny on optimally de-centralized on-site concepts? It looks that in the public sector decision makers tend to select costly conventional, proven concepts. Citizens are still insufficiently aware of the “why and how” of developments in many public domains even though they have to pay the bill; but with respect to making the decisions they generally have to rely on the insights and interests of the “specialists” and (local) politicians. Citizens are so far from sufficiently informed and consequently involved in decision-making, and are generally unable to oppose, particularly when not well organized. Many disastrous decisions in the past can be attributed to that.

The further going back into our past, the more difficult, if not horrifying, were conditions of life for majority of humans; most of the man-made disastrous events can be due to an almost complete lack on scientific insight, catastrophic governance and consequently disastrous inequity. However, mankind becomes slowly aware of the origins of the evil, gradually understands that most of the man-made tragedies can be due to a serious inherent lack of social security for citizens, entrepreneurs, companies, etc., because it leads to self-interested decision-making, to misleading of citizens, to prevention of their involvement in decision-making.

About one and half a century ago, citizens lived in great ignorance with respect to many important aspects for satisfactory conditions of life; science was still in its very initial stages of development, the knowledge in the field of microbiology, biochemistry, chemistry, physics, etc., was negligible. Citizens did not have any idea of the public health risks of wastes, wastewaters and polluted surface water. Residents of Dutch cities at that time disposed excreta in the canals, which at the same time frequently were used as source of potable water. As biological treatment methods for wastewaters and wastes did not exist, hygienic conditions were dramatic. Only in the second part of nineteenth century, things started to improve as a result of implementation of practice directed to collecting human excreta in residences and conveying them out from the neighborhood. Although these activities initially were primarily conducted for use as soil-conditioner and fertilizer to farmers, instead of improving public health conditions, the net result was, however, positive. Only in the second half of nineteenth century the first biological, viz.

anaerobic treatment, systems were developed and implemented. It was the commencement of PuSan and EP; both nowadays are major issues. The consciousness about the crucial importance of a clean environment, the need to attain sustainability in society grew considerably in the last half century, particularly since the publication of the report *Our Common Future* of the Brundtland Commission (1987), with respect to society in general and to the various specific domains, such as PuSan and EP. Gradually the opinion seems to evolve that in these domains sustainability is within reach. A growing group of “specialists” in the field of waste and wastewater treatment is convinced that AeWT as core wastewater treatment method needs to be substituted by AnDi and AnWT treatments, supplemented with the adequate complementary methods. However, developing sustainable EP concepts/systems is just the first step; the second comprises their proper and timely implementation, and this is at least as difficult as it implies a drastic change. From practice it is learnt that the substitution of well-established concepts/technologies, if they are very expensive, complex and in essence non-sustainable, for innovative more sustainable alternatives is extraordinarily difficult. The reason for that generally lays not in any deficits of the innovative technology, but is sociological in nature. It can be attributed to the fact that established institutions, companies, and groups commercializing the traditional established systems generally do not want to give up their privileged position. A major bottleneck on the route to sustainability is that private interests generally prevail over those of the society as a whole. On the other hand, as will be elucidated below, sometimes the private (industrial) sector takes the lead in the implementation of innovative sustainable systems/concepts, like AnWT systems as primary wastewater treatment; although the public sanitation sector is far behind, it irrevocably needs to follow.

2. Roots of Modern High Rate AnWT

2.1. Historical aspects of PuSan with AnDi system (e.g., McCarty, 2001)

The first recognition that anaerobic biological processes could represent an effective method of converting waste organic matter into methane can be attributed to Volta (Barker 1956). He showed in 1776 the formation of “combustible air” from sediments in lakes, ponds, and streams. Eighty years later Reiset observed methane formation in decomposing manure piles and he proposed to study this process in order to understand the decomposition of organic matter (Buswell and Hatfield 1938). The first full-scale application of the AnDi process, i.e., the Mouras’ Automatic Scavenger, was used for treating domestic wastewater in about 1860 (Moigno 1881, 1882). In 1890–1891 W. D. Scott Moncrieff constructed a tank with an empty space below and a bed of stones above, consequently a hybrid of a tank digester and an anaerobic filter (AF). The wastewater of 10 people entered the tank and then passed up through the AF system, resulting in a great reduction in sludge volume. Unfortunately, at that time it was almost completely a black-box system, although the researchers observed the development of a thin bacterial film covering the stone; they indicated, and likely the first to do so, the advantages of retaining wastewater solids for a period of time in order to achieve hydrolytic or bacteriolytic action on waste solids for the conversion of a portion of the organic matter into inoffensive gases or soluble compounds that pass out with the wastewater. Already in 1893!

The first septic tank (patented) was installed in 1895 by Donald Cameron in Exeter, England, treating successfully about $230 \text{ m}^3 \cdot \text{d}^{-1}$ of wastewater initially and the entire city’s wastewater two

years later. Moreover the gas was collected and used for heating and lighting. Similar systems were designed in 1894 by A. N. Talbot for Urbana and Champaign, Illinois in the USA in 1897 (Buswell and Hatfield 1938).

In 1904, a new two-stage anaerobic process was put into operation at Emscher, Germany, in which the suspended solids settled into a separate digestion compartment, the so-called Travis tank (Metcalf and Eddy 1915). In 1905, Karl Imhoff modified the system in order to prevent wastewater flowing through the hydrolyzing chamber, where the sludge was allowed to stay for a period, from a few weeks to several months, in order to make it inoffensive upon withdrawal. The Imhoff tank greatly reduced the cost of sludge disposal and became quite popular (Metcalf and Eddy 1915). However, since the system appeared to be not the complete solution to wastewater treatment, efforts began with separate digestion of sludge (Imhoff 1916); but the system became practically successful only around 1927 with a (first) sludge-heating apparatus in a separate digestion tank at Ruhrverband installed at Essen-Rellinghausen (Imhoff 1938). From then onwards the application of separate digestion grew rapidly in popularity, particularly in larger cities.

The value of generated methane was generally recognized. In addition to its use for heating digesters, applications were found for other purposes as well. In 1923, methane was collected on large scale by the Emscher genossenschaft and delivered to the municipal gas system at the Essen-Rellinghausen plant (Imhoff 1938). In 1927, the Ruhrverband utilized the sludge gas in Iserlohn and then in Essen-Rellinghausen in order to generate power for a biological treatment plant, and the cooling water from the motors was used for heating the digestion tanks. Such use of digester gas is now common practice at wastewater treatment plants throughout the world. By the 1930s, many cities in Germany added compressors in order to store the gas in steel cylinders for use as a motor fuel (Imhoff 1938). This practice also has been used on and off in modern times. Along with these applications, there were several studies then dealing with the full-scale application of separate anaerobic sludge treatment process which resulted in sufficient understanding to accept its wide scale application by the end of the 1930s. However, the basic understanding of the anaerobic digestion process, including the microbiology, biochemistry, and consequently the process technology, was still so poor that the application of anaerobic wastewater treatment (AnWT) could not take off in these years. Interest on AnWT, despite the initial satisfactory results of the AF systems, was almost completely lost in the époque around 1930 in favor of the first-generation aerobic wastewater treatment (AeWT) systems, which were better understood and therefore considered as much more feasible, effective, and robust in operation.

2.2. Historical aspects of high-rate AnWT

The development of modern high-rate AnWT systems for treatment of low and medium strength wastewaters began in the sixties with the anaerobic filter (AF) system at the Stanford University by McCarty and co-workers (McCarty 1964; Young and McCarty 1969). Famous is his statement: *Anaerobic wastewater treatment didn't enjoy the popularity it truly deserves* (McCarty 1964). Besides the re-introduction of the AF system, McCarty made great contributions to the improved understanding and applicability of AnWT, and to the recognition of the crucial importance of bacterial immobilization, i.e., their ability to aggregate in flocs or biofilms. Although McCarty's contributions were crucial for the development and implementation of AnWT, the USA somehow has not found real acceptance of modern AnWT technology, and its funding of research in this

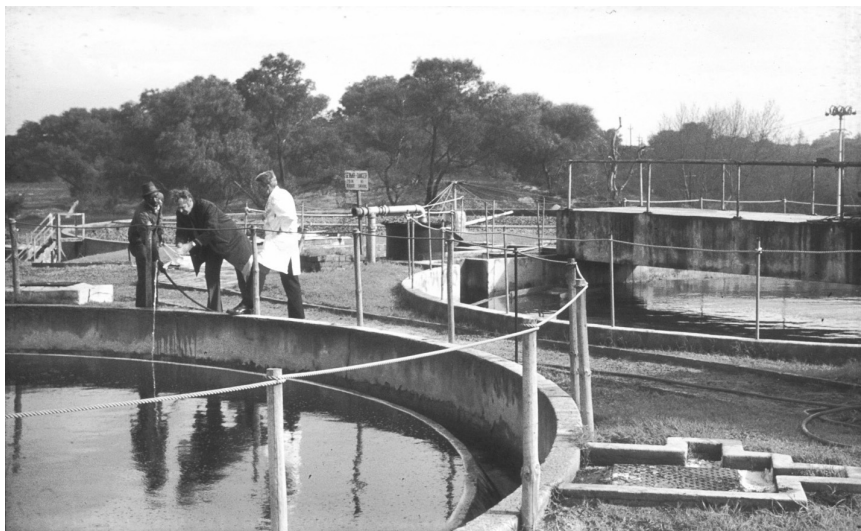


Fig. 1.1. The reversed flow Dorr-Oliver Clarigester in Stellenbos treating wine distillery wastewater, which was full with granular sludge (1980).

field has remained marginal. The main reason for that lies in the extremely reluctant attitude of the established water pollution control sector; any alternative of the conventional AeWT tackle is rejected.

In South Africa, AnWT had already had some “credit” in the fifties as a result of the rather successful application of the so-called “reversed flow Dorr-Oliver Clarigester” system (Fig. 1.1) for the treatment of high-strength industrial wastewaters (Stander 1950, 1966). However, the process was still very poorly understood in all aspects, including microbiology, biochemistry, and particularly reactor operation. In the late sixties and early seventies attempts were made to improve the situation. Fundamental research of microbiology and biochemistry was initiated (e.g., Tourien *et al.* 1967; Thiel 1969; Kotzé *et al.* 1969), along with applied technological research (Simpson 1971; Pretorius 1971). However, like in the USA, the AnWT technology did not take off; in fact, almost all the emphasis in South Africa was soon put on the development of modern AeWT systems, such as the successful biological phosphate removal process.

In Europe, contrary to the USA and South Africa, the interest in AnWT remained marginal until the early seventies. In April 1970, the great breakthrough came resulting from the comprehensive investigations at the Agricultural University in Wageningen and the development of the upflow anaerobic sludge bed (UASB) reactor. Since then, the status of AnWT changed dramatically (Lettinga *et al.* 1980).

3. Development of Anaerobic Upflow Sludge Bed Systems

3.1. Conventional UASB (Lettinga 1995)

Inspired by McCarty’s work but completely ignorant of the “ins and outs” of biological wastewater treatment methods, I moved into the field of AnWT when I started my career at the Wageningen University. With a chemical engineering background and specialization in physicochemical

treatment of radioactive wastewaters, unprejudiced with respect to any biological treatment system, I started investigating the feasibility of the AF system, copying from McCarty's design, for the treatment of wastewater of the potato starch industry, which had since many decades seriously polluted surface waters in the North-East of the Netherlands. The results obtained in the laboratory with diluted freshly prepared potato juice solutions were very promising and challenging. First of all, high treatment efficiency was achieved at volumetric loads exceeding $10 \text{ kg-COD}\cdot\text{m}^{-3}\cdot\text{day}^{-1}$, and the startup proceeded smoothly. Furthermore, quite importantly, like Young and McCarty (1969) we observed the formation of a highly active and extremely well-settling sludge. We hoped these findings would convince the potato starch company to move into further research directed toward the implementation of AnWT at their factories, more particularly to the even more promising UASB reactor developed in our laboratory (Lettinga *et al.* 1980). Like the AF system, the UASB reactor has a simple design, but it looked applicable for a much wider range of wastewater (including some containing partially insoluble particulates) with substantially higher loading potentials and is likely cheaper in investment and operation. Although at first sight the UASB reactor resembles the South African "reversed flow Clarigester" system, it in essence deviates considerably in design and in mode of operation. Following the laboratory and bench-scale investigations in 1971–1972, the feasibility of the UASB reactor concept was successively demonstrated at 6 and 30 m^3 pilot plants for (although not the potato starch wastewater as we hoped) sugar beet wastewater, which was substantially less complex than the potato starch wastewater. This work was made in close co-operation with a Dutch sugar beet company (CSM) with involvement of researchers of Wageningen Agricultural University, Amsterdam University and Delft Technical University, and with substantial financial support from the Dutch government. The first 200 m^3 demonstration reactor was put in operation in 1976 at a sugar beet factory near Amsterdam, and at the same location one year later the first 1000 m^3 full-scale UASB reactor and the following year the second at the sugar beet factory in Breda (Fig. 1.2). Scaling up of the UASB system to 1000 m^3 was achieved within only 5–6 years. Starting from the mid-seventies, the feasibility of the system was assessed for numerous types of effluents of agro-industries, including the complex potato-starch wastewater during 1979–1981. Based on the successful demonstration and implementation of the system for a number of agro-industrial wastewaters, the Dutch government forced the board of potato Starch Company to try out the system (the alternative treatments tried out by the industry before then appeared to be far too complex and expensive). However, contrary to our results of laboratory experiments conducted with diluted freshly prepared potato juice solutions, the treatment of real wastewater appeared quite problematic. It was in fact barely feasible only after the continuous supply of a trace element cocktail to the raw wastewater; we discovered the significant effect of trace elements in preliminary experiments in preceding years and in comprehensive continued still on-going investigations (Zandvoort *et al.* 2005).

The sudden development of this niche for AnWT in Europe can be attributed to a coincidence of reasons: (i) the implementation of strict legislation of effluent discharge in 1970 in the Netherlands, which led to a strong increase in the interest from the polluting industries in low-cost treatment systems, (ii) the established water pollution control industry was then completely directed to AeWT and quite overloaded, and was also ignorant, and in fact prejudiced regarding the potentials of AnWT, (iii) the very smooth and successful demonstration of the UASB system, (iv) the considerable financial support from the Dutch government to improve the insight in various aspects of AnWT, i.e., the microbiology, biochemistry, and reactor and

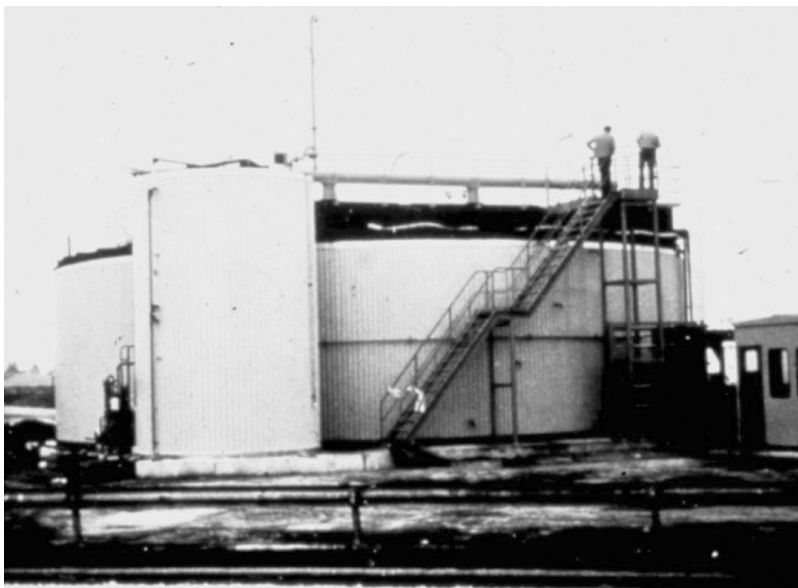


Fig. 1.2. Full-scale UASB treatment of effluent of a CSM (company) sugar beet factory in the Netherlands (1976).

process technology, and (v) the establishment of new contractors moving into the field of modern AnWT. The interest in application of high-rate AnWT systems for the treatment of industrial wastewaters was not just restricted to the traditional mesophilic conditions but also developed for thermophilic (van Lier *et al.* 1992, 2001) and psychrophilic conditions (Rebac *et al.* 1998). Moreover, along with the steeply increasing interest in application of the UASB concept for the traditional anaerobic treatment, other applications of the UASB concept came in picture, such as biological sulfate reduction, de-nitrification, and for innovative micro-aerobic (post-)treatment systems, and more recently even for aerobic treatment systems, for final polishing of the effluent and/or nitrification.

Following the success in the industrial sector, the next big challenge for us was the issue to assess the feasibility of the UASB system for raw domestic sewage pre-treatment. Based on preliminary research conducted in sixties and early seventies in the USA and South Africa, we started in 1976 comprehensive laboratory, bench and (0.03–6 m³) pilot plant investigations for sewage first at temperatures exceeding 20 °C (tropical conditions), and later since the late seventies for temperatures in the range of 10–20 °C. Since the investigations directed to applications under tropical conditions were very promising, the Dutch government provided financial support to continue the comprehensive feasibility studies at a 64-m³ demonstration plant in Cali, Colombia during 1981–1986. The results clearly demonstrated the big potentials of the UASB system for that purpose, and also for application in decentralized settings. These positive findings (Louwe Kooijmans *et al.* 1985) led to the construction and startup of a number of big full-scale UASB installations in Colombia (Schellinkhout and Collazos 1992) and India (Wiegant 2001), once again by the financial support of the Dutch government.

The efforts to demonstrate the feasibility of the one-step UASB system for raw sewage pre-treatment under the moderate Dutch climatic conditions were less successful, i.e., not sufficiently attractive to promote its full-scale implementation, but on the other hand, for us, not too

“poor” to terminate these investigations. It ultimately led to the development of an integrated UASB-AnDi system, in which the complementary AnDi step serves for: (i) the mineralization of the poorly stabilized sludge accumulating in the UASB reactor; and (ii) maintaining a sufficiently high methanogenic activity in the UASB reactor by returning part of the digested sludge into it (Mahmoud *et al.* 2004a, b). This integrated UASB-AnDi system, though slightly more complex in operation and design, offers attractive potentials for applications in moderate climates. It may be particularly attractive as a pre-treatment for toilet and kitchen wastewaters collected with vacuum systems in so-called decentralized sanitation and reuse (DESAR) settings, i.e., the optimally sized on-site settings, such as separate communities, hospitals, hotels, schools, apartment buildings, etc. This DESAR concept is directed not just to protect the living environment from pollution, but also to particularly recover useful byproducts (biogas, fertilizers, soil conditioners, etc.), and to prevent the installation of expensive transport systems (Kujawa-Roeleveld and Zeeman 2006; Zeeman *et al.* 2008). The interest in this innovative concept has gradually been growing in Europe. In China substantial progress has been made in the last decades with the implementation of community on-site AnWT systems in the public sector, especially in rural areas (Wang 2004).

Undoubtedly one of the very challenging features of the UASB system comprises its ability to generate granular anaerobic sludge, i.e., a sludge consisting of mechanical robust, very well settleable and biologically active bacterial aggregates up to about 3 mm in size. This peculiar phenomenon, which had in fact been noticed by Young and McCarty (1969) in their AF systems, became since mid-seventies a major joint research topic at our university between the Departments of Environmental Technology, Microbiology, and Physical-Colloid Chemistry (e.g., Hulshoff Pol *et al.* 1981, 1983; Grotenhuis *et al.* 1991; Visser *et al.* 1993; Alphenaar *et al.* 1993). Its immense potential impact for practice and scientific challenges was soon recognized in a wide circle, and became since the eighties a major issue of research at many other universities worldwide. It has led to significantly improved insight in the “whys and hows”, although not yet to a complete general consensus (McHugh *et al.* 2003; Hulshoff Pol *et al.* 2004). Still numerous challenging questions remain to be elucidated (Lettinga and Hulshoff Pol 2002).

3.2. The EGSB system

Soon after the “discovery” of the renowned features of granular sludge, comprehensive investigations were directed to the development of the EGSB system. The EGSB reactor relies on: (i) the exclusive use of granular sludge, (ii) operation under conditions of a slight bed expansion, and, particularly, (iii) the expectation that granules remain stable and will smoothly augment. (Lettinga *et al.* 1980; Lettinga 2010; Kato *et al.* 1999; Rebac *et al.* 1998). The EGSB system offers great potentials: it can (i) accommodate very high organic and hydraulic loadings, (ii) treat very low-strength ($\text{COD} < 150 \text{ mg}\cdot\text{l}^{-1}$) wastewater, (iii) be feasible for low-strength acidified wastewaters under psychrophilic conditions (even at 4–10 °C), and (iv) be capable of treating wastewaters containing lipids and toxic/inhibitory compounds like formaldehyde, lauric acid, etc.

The EGSB reactor concept became popular in the last decades for treatment of a variety of industrial effluents. However, despite the many satisfactory full-scale experiences, still substantial improvements can be realized in order to improve its stability and to extend its applicability. Particularly further research needs to be done to improve the insight into the mechanisms under-

lying specific aspects of the “granular sludge phenomenon”, viz., maintaining a sufficiently high stability, the smooth augmentation, and the possibilities to manipulate the bacterial composition, i.e., how to incorporate new organisms (Lettinga 2010).

3.3. Other high rate reactor designs

Two systems comparably very similar to EGSB were developed in the eighties: the anaerobic fixed-film bed system developed in the USA (Jewell *et al.* 1981; Switzenbaum and Jewell 1980) and the expanded-bed version of the anaerobic fluidized bed developed in Belgium (Binot *et al.* 1983) and in Spain (Iza *et al.* 1987). Both these systems rely: (i) on bacterial film attachment to small carrier materials supplied to the reactor, (ii) on the agglomeration of these attached biofilm grains, and (iii), like the EGSB system, on their augmentation.

Attempts (e.g., Heijnen 1988) to develop a completely fluidized anaerobic bed system failed; as a matter of fact, this system inherently cannot be successful, because maintaining a completely fluidized bed requires uniform (in shape, size, and density) bio-film particles, or agglomerates. That is impossible; irrevocably sludge bed segregation will occur.

Other innovative developments on anaerobic sludge bed systems in the eighties and nineties comprised the anaerobic sequencing batch system developed by Dague (Zhang *et al.* 1997), the anaerobic baffled reactor system which originally was developed in the USA (Barber and Stuckey 1999), and various hybrid reactor systems.

4. Place of AnWT in EP

Since the mid-seventies, anaerobic treatment has received significantly increased acceptance worldwide, although countries like the USA and South Africa have so far remained reluctant. The idea gradually finds acceptance that we urgently need a much more sustainable tackle in PuSan and EP, meaning that we need much more economical systems and concepts which enable a maximum extent of waste valorization, and which in due time can lead to all kinds of modern urban agricultural practices. The insight is growing that AnWT and AnDi processes indeed should be the first, and in essence the major, treatment step in what we consider as a really sustainable EP-tackle (EP_{sus}); they are the core step in the mineralization route of organic matter in nature. This *Natural Biological Mineralization* (NBM) route is exactly the tackle to be followed in waste and wastewater treatment; it virtually leads to the approach needed for EP_{sus}. After the AnDi/AnWT step, the subsequent treatment steps in the NBM tackle are successively the micro-aerobic and aerobic polishing steps, which may include, if necessary, the full oxidation of reduced S- and N-compounds. The innovative micro-aerobic steps, which rely on unique bio-conversions occurring under conditions of very low oxygen supply or concentrations, are effective in the conversion of highly reduced compounds, like H₂S and volatile organic S-compounds (Buisman *et al.* 1990; Janssen *et al.* 1997; van Leerdam 2007; Sipma *et al.* 2003) in the raw wastewater or generated in the preceding AnWT step (Fig. 1.3).

The NBM tackle offers the following advantages over the conventional AeWT-based approach:

- Energy generating, instead of energy demanding;
- Resource recovery, i.e., waste valorization and urban agricultural practices;



Fig. 1.3. Full-scale UASB plants (rectangular and circular installations in the center part of the photo) treating the combined reuse paper wastewater of three factories, and conventional aerobic post-treatment (right upper part of photo) and micro-aerobic biogas-treatment facilities (in a small separate building positioned between the AnWT-installations) in the city Eerbeek, Netherlands.

- Very low volumes of excess sludge which are concentrated and well stabilized;
- High organic and hydraulic volumetric loads, resulting in very low space requirements;
- Simple in operation and maintenance, and consequently hardly depending on specialists;
- Low in capital investment, as well as operational and maintenance costs;
- Use of conventional, plain equipment which can be generally manufactured locally;
- Long life-time of installations and auxiliary equipment;
- Anaerobic sludge can be stored unfed for long periods of time without losing its activity;
- Applicable at almost any scale, and at almost any location;
- Very robust, independent of any complex infrastructures, e.g., for power supply;
- Almost absence of any malodorous problems;
- Avoid the formation of recalcitrant compounds (e.g., humic acids); and
- Efficient in degrading various recalcitrant compounds, such as azo dyes, polyaromatic compounds, and nitro-aromatics.

These advantages enable industries to accomplish an almost complete closing of water and matter loops, especially when the NMB methods are implemented in settings which focus on clean water saving practices and minimization of transport, consequently on optimal de-centralized settings. But this is true not merely for the industrial domain, but also for the agricultural and PuSan sanitation domain. And this fortunately is gradually happening. Following the success in the industrial sector, the successful demonstration of AnWT for sewage pre-treatment in tropical regions, and the proven potentials of innovative NBM-based post-treatment meth-

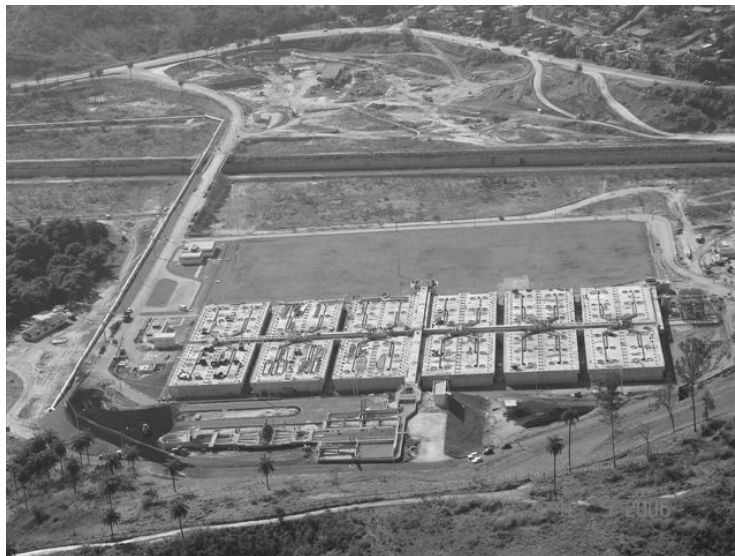


Fig. 1.4. Full-scale UASB-Plant at Belo Horizonte, Brazil, consisting of 12 reactor modules, (pre)treating raw municipal wastewater for 1 M inhabitants at $1.8 \text{ m}^3 \cdot \text{s}^{-1}$. (photo obtained from C. Chernicharo).

ods, this approach irrevocably will find worldwide acceptance in the PuSan sector. At present Brazil is in the frontline of such approach (Chernicharo 2006; Foresti *et al.* 2006) (Fig. 1.4). The potentials of domestic sewage pre-treatment by modern AnWT systems indeed are enormous, and certainly this is not merely true for tropical regions; the NBM tackle also can profitably be applied in subtropical regions (Mahmoud *et al.* 2004b), especially during summer season in touristic regions where the population during the season can reach tenfold higher than other seasons. Implementation of the NBM concept, along with adequate wastewater collection practices and transport minimization can and will lead to very substantial savings, both in investment and in operational costs.

5. What Could the Future Bring?

With the NBM-based treatment concept, most of the tools for attaining a sustainable tackle in PuSan and EP lay ready on the shelf. Combined with adequate measures and technologies directed to prevention of pollution, e.g., application of clean water saving collection practices for liquid and solid residues as well as minimization of transport, the optimal conditions for a really sustainable environmental protection and public health care in communities can be realized in near future. By putting the focus on a step-wise implementation of optimal DESAR concepts, which are directed to closing loops of water and other matters in residential communities, at the industrial sites, in separate buildings or clusters of buildings, or at farm-scale, a maximum of valorization of residues can be achieved at a minimum of input of resources and it can promote urban agricultural practices. A very important step made in that respect comprises the raising interest of hospitals, at least in the Netherlands, to become completely self-sufficient in treating their hazardous waste and wastewaters. Very likely, hotels, restaurants, schools, etc. will soon

follow, if it can be proven that these systems are economically profitable and may lead to a high extent of self-sufficiency, as is the case for industries.

Moreover, these NBM methods, especially when supplemented with adequate physicochemical methods, are also ideally suitable for treatment of polluted water, solid residues, and gases, as well as for the decontamination of polluted soils. Contemporary and future generations can make a major contribution toward a much higher sustainability in society in various domains.

A question coming up is: Can anything prevent us from advancing in that direction of EP_{sus}? Judging from the significant progress made in the industrial sector in the last decades, the answer is simply “No”. Politicians, decision makers, consultants, and engineers have gradually become much more confident that the issue of EP_{sus} is no longer a dream, but a well achievable option. The bottlenecks certainly lay not in technological deficits or lack of appropriate EP_{sus}-concepts, but predominantly can be found in all kinds of sociological factors, i.e., too much tunneling in the approach, monopolization of decision-making in the sector by the civil engineering discipline, too dominant interests of established private business in existing methods and concepts. But certainly there exists also a general lack on long-term vision and/or courage from the side of public policy makers. And last but not least, the involvement of citizens in decision-making is still far too little, and the need to be adequately informed about what is going on in the development of anaerobic technology. Then, the extreme reluctance of the established pollution control would ultimately vanish, and these concepts irrevocably will find their way into the public domains of sanitation.

In various countries the first steps have been made in the PuSan domain, particularly in Brazil where the federal government stimulates the implementation via the so-called PROSAB program. This to some extent also happens in India, Mexico and slowly even in European countries like Germany and the Netherlands (Kujawa-Roeleveld and Zeeman 2006). However, despite that, it will be a long and difficult way to go. The expulsion of all kinds of evil heritages needs prolonged periods of time and tremendous effort. But, it will happen; the benefits of EP_{sus} concepts simply are too pregnant and too challenging. This issue is not only just a clean living environment, but also a realization of innovative forms of urban agricultural practices, more integration between urban and rural regions, and achievement of a significant higher extent of self-sufficiency in many other domains (Lettinga 2004). Consequently, there is hope that gradually the general insight will establish that Brundtland’s envisaged drastic social changes for achieving “real” sustainability in society at global scale, merely can be attained when our enormous scientific and technological achievements are optimally employed for the well-being of all citizens.

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