Front. Environ. Sci. Engin. China 2010, 4(2): 123–134
DOI 10.1007/s11783-010-0028-1

FEATURE ARTICLE

Challenges of a feasible route towards sustainability in environmental protection

G. LETTINGA (✉)

LeAF-foundation, Sub-department of Environmental Technology, Wageningen University, P.O. box 8120, 6700 EV, Wageningen, Netherlands

Abstract Anaerobic processes for treatment of low and high strength wastewaters and solid wastes constitute the core method in the natural biological mineralization (NBM) treatment concept. When adequately combined with the complementary NBM-systems and modern clean water saving practices in wastewater collection and transport, they represent a feasible route to sustainable environmental protection (EP_{sus}), in essence even towards a more sustainable society. Despite the development and implementation of modern high rate Anaerobic Wastewater Treatment (AnWT-) systems and complementary innovative NBM-processes, the considerable progress made since the seventies in fundamental insights in microbiology, biochemistry and process technology, still numerous challenging improvements in the NBM-field can be realized. This contribution is mainly based on the insights attained from wide ranging literature evaluations and the results of experimental research conducted by numerous PhD students who participated in our group over the last four decades. An attempt is made here to identify major facets on which an improved insight can, and consequently should, be obtained in order to accomplish more optimal operation and design of various types of Anaerobic Degradation (AnDeg-) processes.

Keywords sustainability, environmental protection, anaerobic treatment, micro-aerobic treatment, natural biological mineralization concept, traces elements, macro-nutrients

1 Introduction

It would be fortunate if mankind could succeed in accomplishing a fully sustainable protection of the environment (EP_{sus}) on a global scale. The habitats for flora, fauna and humans need to be protected through the lowest possible input of resources, labor, and capital by using technologically and economically affordable, plain and robust concepts and technologies. Since practically all the tools required for the implementation of this vision lie ready 'on the shelf', it is an imperative to implement these EP_{sus} concepts. There are certainly reasons for optimism. However, at the same time there are doubts as well. The principal question is "Are we capable of implementing them in time?". And in the case that we are, then we need to ask "Is the extent of environmental deterioration already not too dramatic?", and "can we get the mechanisms under control, which lead to excessive world population growth?", and "what actions need to be put in place to mitigate extreme urbanization and the dramatic deterioration of living conditions, in, for example, rural areas?".

More than 20 years ago the Brundtland Committee [1] emphasized the need to realize drastic changes in society. Severe threats in society need to be eliminated, such as continued prevailing extreme poverty, dramatic environmental deterioration, and the excessive growth of world population. 'Sustainability in Society' stands for "Absence of man-made scarcity with respect to all primary needs and prevention of any form of wasting". Figure 1 depicts the high ambitions of what Brundtland meant by '*Sustainability*'. In all respects Brundtland goes much further than the superficial interpretations of the vast majority of contemporary political leaders, multinational enterprises and many scientists. In essence Brundtland's message is that scientific, technological and cultural achievements of mankind should be made available for all world citizens without any restrictions.

Is it an almost hopeless mission to achieve sustainability in society? Not entirely. History teaches that drastic beneficial shifts occasionally occur when conditions in society suddenly become mature for change. This may happen as a result of any 'success' on the route towards greater sustainability, as for instance in the field of EP. Once citizens understand that such a progress indeed serves the well-being of all people, they will become eager

Received December 11, 2009; accepted January 26, 2010

E-mail: Gatze.Lettinga@wur.nl

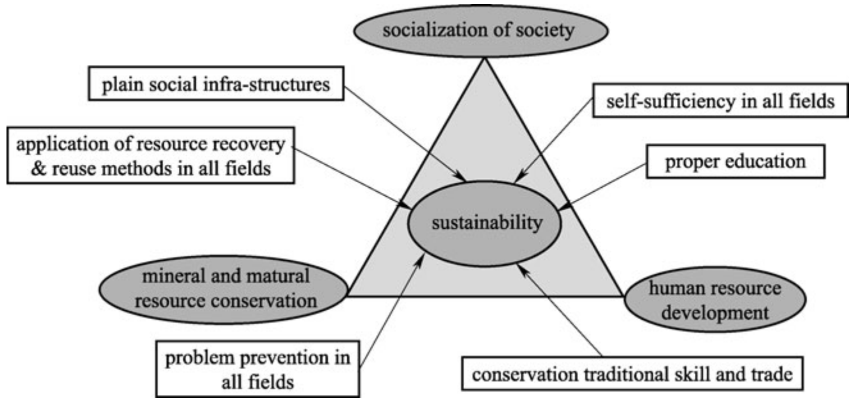

Fig. 1 Three 'pillars of sustainability' in society and some tools to achieve it

to force political leaders to initiate drastic changes. And one of the more crucial needs for the quality of life of citizens undoubtedly comprises a clean and secure living environment for all people, i.e., EP_{sus}. In order to make progress in achieving the high goals of EP_{sus} the focus needs to be put on i) 'Pollution Problem Prevention (P_3)' and ii) the achievement of the recognition of a maximum of valuation of domestic residues ('wastes') and optimal reuse of effluents (treated wastewater) from treatment systems. As a result of preventing the waste of clean water in the collection and transport of waste (water), and in order to achieve the valuation issue, conventional treatment systems need to be substituted by systems based on the Natural Biological Mineralization (NBM) route [2,3].

Anaerobic Wastewater Treatment (AnWT) processes comprise the core method in NBM-treatment concepts, because i) they offer the unique advantage of realising a maximum recovery of resources from wastes (e.g., energy and nutrients), while ii) at the same time they lead to substantial savings of fossil energy, compared with conventional waste treatment technologies. Consequently, in order to achieve progress toward EP_{sus} we need to substitute conventional 'Centralized Sanitation' concepts (CENSA) for modern "Decentralized Sanitation and Resource Recovery & Reuse" concepts, utilizing the very promising $DESAR_3$.

2 Features of a sustainable environmental protection (EP_{sus})

The P_3 and R_3 pillars of EP_{sus}, imply the focus of the EP-measures to be taken in society merely on tackling pollution problems, which originate from the inevitable natural disasters, e.g., earthquakes, floods, storms, future drastic changes in climate, etc. In combating environmental pollution, exclusive use should be made of robust concepts and technologies; history teaches that disastrous environmental damage generally originates from inevitable natural disasters and/or from all kinds of man-made catastrophes, frequently due to the collapse of far too vulnerable EP-facilities or their destruction on purpose, e.g., in military events. Therefore, robust methods of environmental protection are required, which neither rely on advanced and expensive transport and treatment technologies, nor on complex infrastructural provisions, such as the power supply and highly specialized technicians or institutions.

In nature, wastes do not exist; almost everything is part of the eternal life cycle. It would be wise to imitate nature, particularly in the protection of the environment, for example by closing water and material loops through using the economically most affordable and sustainable technological and conceptual means, all directed on waste valorization. When realized at on-site and/or at regional level, it will enable communities, towns, villages, cities and regions, and even countries, to accomplish a maximum extent of self-suffienciency in EP; this then will have a very positive spin-off in other fields. Such an EP_{sus}-tackle obviously requires a holistic attack of the 'real' problems. In order to achieve that, all presently available relevant knowledge needs to be transferred free of charge to potential users in order to enable them the implementation of the required systems/concepts properly. Then, concomitantly, all kinds of challenging opportunities will evolve in other fields, for instance in local (urban) agricultural practices. In this way, step by step a more sustainable society will be attained, enabling all citizens to employ presently available technical, scientific and cultural achievements. As a result humanity can ultimately release itself from serious threats from the obscure past such as its immense social insecurity, a disease inherited from the past! However, all kinds of established groups, institutions, etc., generally are extremely reluctant to abandon their privileged positions; this seriously frustrates the smooth implementation of the EP_{sus}-concepts. The latter is particularly true for the public sanitation sector. The main bottlenecks for implementation in this sector can be found in the lack of 'political' willingness and/or courage, absence of proper 'market incentives' and/or lack of a 'well established logistic, educational and decision making infrastructures'. Moreover, despite the enormous potentials of the envisaged EP_{sus}-tackle, the industrialized world tends to look for highly advanced, generally expensive solutions, which leads to more rather than less dependency on specialists and vulnerable infrastructures like that of supply of energy; this virtually is the case for almost any sector in society. These developments are enhanced by a dramatic lack in social and entrepeneuring security in society. The question is how to escape from this threat.

3 NBM-route based waste (water) treatment tackles in EPsus

It is well known that under natural conditions the recuperation of polluted surface waters proceeds via a sequential anaerobic, micro-aerobic and fully aerobic biodegradation of the pollutants, on the basis of processes proceeding according to the biological C-,N and S-cycle, together with associated chemical and physical processes. As clearly demonstrated in 'aging experiments' with sewage samples [4] this Natural Biological Mineralization (NBM) route of organic matter, depicted in Fig. 2, ultimately leads to the complete recuperation of the polluted water. However, at the same time this technologically undemanding R_3-directed treatment concept for wastes and wastewaters enables recovery of useful byproducts, provided that those responsible are capable of deploying them wisely. In essence the various NBM-treatment systems are available for use, although their microbiology and (bio) chemistry may be designated as 'complex', and certainly not fully understood yet. Perhaps some of them never will be understood fully either, but working with a partial 'black box' does not represent a real bottleneck for optimal applications. The NBM-treatment route meets practically all criteria for EP_{sus} [2].

Apart from the fact that NBM-treatment systems enable an almost complete removal of organic pollutants from the wastewater(s), they provide ideal conditions for conserving/recovering resources in the form of fertilizers, soil conditioners and renewable energy. This specific feature can be attributed particularly to the renowned potential of Anaerobic Degradation (AnDegr) steps, consisting of:

i) Anaerobic digestion (AnDi) processes, which convert biodegradable organic compounds into a mixture of methane and carbon dioxide,

ii) Sulfate reduction (SuRe) processes, which take care of the conversion of oxidized forms of sulfur into H_2S,

AnDegr-processes constitute the ideal mineralization tackle for organic matter; they therefore should constitute the first treatment step. AnDi-systems for stabilizing very high strength wastewater(s) and/or slurries can consist of conventional low or high rate digesters, or innovative high rate digesters complemented with specific physical-chemical pre-treatment systems. For the treatment of medium and (very) low strength wastewaters, modern high rate anaerobic wastewater treatment (AnWT) systems have become available since the ninety-seventies; so far, generally they have found application mainly in 'one-step' reactor configurations. Nowadays, the most popular AnWT-systems comprise stationary upward or downward flow Anaerobic Filter (AF) systems, (re)introduced in the sixties in the USA [3,5], and Upflow Anaerobic Sludge

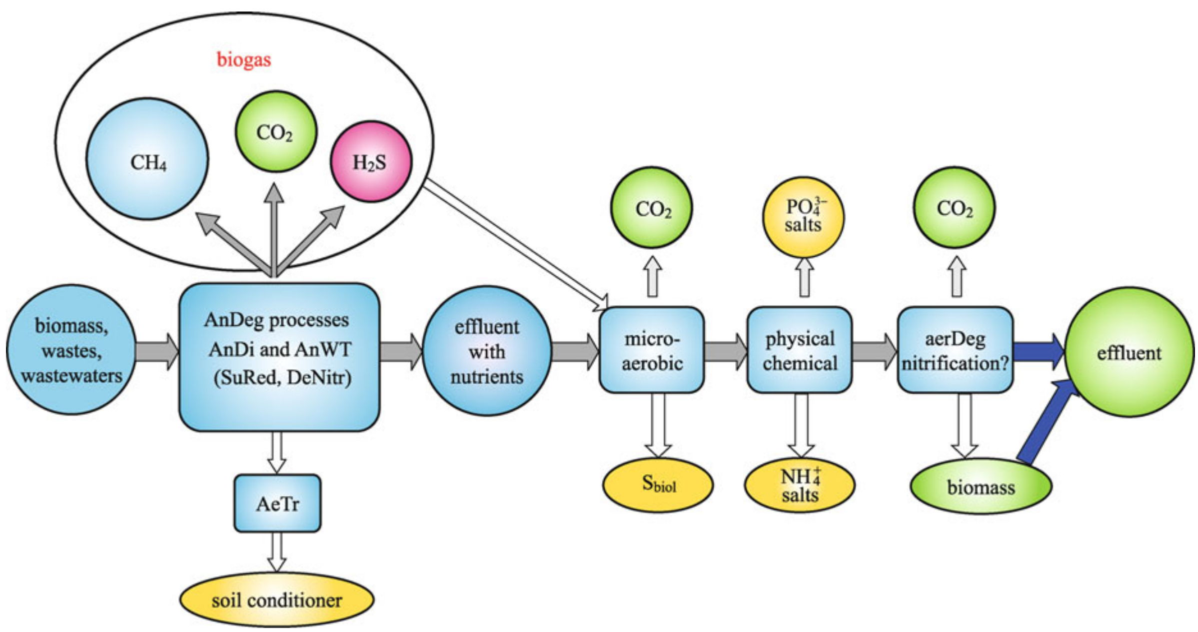

Fig. 2 The natural biological mineralization (NBM) route as treatment concept for waste and wastewater valorization

Bed reactors (UASB), developed in the early seventies in the Netherlands [6,7,8]. The very promising next developments are the Expanded Granular Sludge Bed (EGSB), developed in the Netherlands in the early eighties, and the Attached Fixed Film Expanded Bed (AFFEB) system, developed in the USA [9]. The Sequential Anaerobic Batch Reactors (SABR) and Baffled Anaerobic reactor systems [10,11], and various types of hybrid reactors may also undoubtedly hold out some promise.

These systems, particularly the UASB and EGSB-process [8], have found a wide application for a large variety of industrial effluents, although so far mainly under optimal mesophilic conditions. Since the late nineties these systems have been applied to the pre-treatment of raw sewage in a number of tropical countries. In the last decades insight into the reactor and process technology has improved significantly.

Compared to UASB-systems, EGSB-systems possess significantly better potential for removing toxic biodegradable compounds like lauric and capric acids [12–14], higher fatty acids [15–17], formaldehyde [18,19] and/or complex compounds present in paper pulping effluent [20]. This feature of the EGSB-reactor system which is very attractive for practice, can be attributed to i) the significantly better contact attained in EGSB-systems as a result of the high upward liquid velocities and ii) the low concentration of these compounds maintained in the reactor liquid phase as a result of the imposed high effluent (so-called 'upfront dilution') recycle factors. In view of the prevailing high substrate transport rates in EGSB-systems, they even are well suited for the treatment of very low strength wastewaters, i.e., down to about 200 mg COD/L, both under mesophilic and psychrophilic conditions [21–27]. Clear experimental evidence was obtained that the methanogenic activity of the retained biomass still increased under these extreme conditions, indicating that the wash-out of viable methanogenic organisms due to erosion of granules remained exceptionally low! The potentials of the EGSB-concepts therefore look exceptionally promising, provided the stability and the size of the sludge grains can be maintained in the optimal region. The latter condition certainly cannot always be met. Therefore, in specific cases, for example effluents containing triglyceride emulsions, a modified, more sophisticated, Gas-Solids Separator device needs to be installed in order prevent problems due to floating granular sludge [13]. Nevertheless, undoubtedly challenging developments for EGSB-reactor systems lie in front of us.

Although modern versions of high rate AnWT-systems only became popular starting in the seventies, the AF-system already was introduced at the Massachusetts experimental station almost 1.5 centuries ago [5]. The first full-scale AF-system, consisting of a bed of sand, was put in operation at that experimental station in 1887 for sewage treatment. In one of the AF-reactors, up to 89 % removal of the organic impurities was obtained at a pore space detention time of about 8 days; in a second AF-system, using 0.5–2 inch diameter broken stone, 85% organic matter removal from domestic wastewater was achieved at a loading rate of about 2 m/d. However, contrary to 'ancient' AnWT/AnDi-systems of the septic tank and Imhoff tank type and despite the promising results obtained, the AF-system apparently could not conquer the required popularity. Although in essence all these 'ancient' AnWT and AnDi systems at that time were "black box reactor systems", the vast majority of them probably performed reasonably satisfactorily, even despite the presence of volatile obnoxious compounds in the effluent. But undoubtedly many of them suffered from severe overloading. Consequently, they became unwelcome in the neighborhood. Nevertheless, despite their 'bad smell' and complete lack of understanding of the microbiology, and of technological aspects from the side of the sanitary engineering world, their use fortunately has never been abandoned. In many countries and regions these systems still have a very important role in environmental protection. Moreover, it is very likely that promising innovative versions will soon become available, because the insight into the microbiology, biochemistry and reactor technology of the anaerobic digestion process which has been improved very substantially over the last decades. The revival of these systems in modern $DESAR_3$-concepts in the public sanitation sector lies ahead of us. For billions of citizens suffering from lack of any adequate sanitation this is a matter of the utmost importance. But undoubtedly this also will become true for prosperous citizens since everybody ultimately wants a robust and sustainable type of EP.

The major role of the micro-Aerobic Wastewater Treatment ($Ae_{micro}WT$) systems is to accomplish the required first post-treatment, comprising particularly the removal of volatile mal-odorous compounds. These innovative methods constitute the ideal complementary treatment step to AnWT. The idea underlying $Ae_{micro}WT$ is that by supplying minor amounts of oxygen in the anaerobic effluent, a 'perfect' environment is created for a variety of specific micro-aerobic organisms. The organisms will take care of i) the high-rate conversion of reduced (highly odiferous and toxic) S-compounds into elementary sulfur, ii) the removal of part of the remaining, easily biodegradable organic pollutants; iii) the oxidation of specific reduced inorganic compounds (e.g., FeII) and iv) the removal of colloidal matter (including dispersed pathogenic organisms, i.e., via a coagulation and/or biofilm entrapment process. Moreover, since the content of biodegradable matter in the effluent of the anaerobic (pre-) treatment step is low, the $Ae_{micro}WT$ step pairs minor energy demands with a very low excess sludge production. According to the findings of Tawlik et al. [28–30] a one-and/or two-step micro-aerophilic Rotating Biodisk Contactor (RBC-reactor) system is capable of removing dissolved mal-odorous compounds and reduce inorganic compounds efficiently from an anaerobically pre-treated sewage at hydraulic retention time (HRT) values of only 15 min. However, the elimination of soluble biodegradable (COD_{biod}) and colloidal matter, including indicator organisms for pathogens, needs more time, for example in the range of 30–150 min, depending on the quality of the effluent.

Undoubtedly, the major innovative development of the Ae_{micro}WT-system lies in its capacity to convert reduced S-compounds into elementary sulfur [31–37]; the system enables a high rate and low-cost bio-conversion of volatile S-compounds like H_2S and methanethiol from polluted gases, e.g., from Liquefied petroleum gas (LPG) [38–41] and from natural gas and/or biogas. The system is effective up to removal capacities of 50 tons H_2S/day; for higher loads tentatively the well-proven amine/Claus process still looks more attractive [40].

This manipulated oxidative section of the S_{bio}-cycle comprises, when properly combined with its reductive part, an attractive piece of equipment for the remediation of Zn-contaminated soils (already applied at full-scale) and soils likely to be contaminated with other heavy metals. The S_{biol}-cycle is also effective for the treatment of aqueous solutions (acid mine drain water) contaminated with heavy metals and for the treatment of SO_2-polluted air. The elementary biological-sulfur ultimately *recovered* in the process, and comprising one of the many allotropes of elementary sulfur, possesses peculiar features; it is hydrophilic and dispersible in water, can be used as fertilizer, fungicide and raw material in the industry; consequently, it will become an attractive by-product.

The remaining function for aerobic treatment (AeWT) lies mainly in i) the polishing of the effluent of the Ae_{micro}WT step, i.e., the removal of the (very) small amounts of remaining biodegradable matter, and ii) as the nitrification step of dissolved ammonia, in case N-removal should be needed. In the latter case a complementary denitrification step also needs to be incorporated, or possibly better, the innovative systems Anammox process [42]. However, in case when sufficient land is available for agricultural purposes, it will be a much more valuable use of the dissolved nutrients to apply them as fertilizer, e.g. for cultivating biomass in algae or duckweed generating ponds [43,44].

As in the case of the treatment of wastewaters, AeWT-systems should be abandoned as the primary step for the 'stabilization' of solid organic wastes/residues; conventional composting systems do not lead to best use of solid organic residues. However, subsequent to a first AnDi-step, they can be quite useful as composting step. Regarding the merits of the NBM-concept it is obvious that old-fashioned sanitary engineering practices like land-filling need to be abandoned, due to potential pollution problems.

In order to achieve an optimal value for the pollutants, NBM-systems can be supplemented/complemented with proper physical-chemical (PC) removal/recovery steps, e.g., stripping-absorption processes for ammonia (and phosphate) recovery, precipitation processes for insoluble phosphate and ammonia-salts (struvite), membrane processes and UV-radiation in order to produce potable or process water.

The NBM-treatment concept, at some time in the future, will undoubtedly bring a definite end to episode of the 'advanced' AeWT secondary treatment tackle and the 'clean water wasting' centralized sanitation (CENSA) approaches in the public sanitation (PuSan) sector. These conventional systems simply suffer from too numerous serious drawbacks [2], they are far too complex and too expensive, and for those reasons are often abandoned in developing countries soon after having been installed, with all the dramatic consequences for the environment! NBM-systems are simply by far superior (see Table 1– Advantages).

The established 'advanced AeWT system' is a heritage from the late nineteenth and early twentieth centuries; the first activated plants were put into operation in 1917 in Manchester and in Houston [11], and the first trickling filter was already established in 1893 in the UK; the system became particularly popular in USA. The AeWT-system superseded the promising house and community on-site AnWT pre-treatment approach introduced around 1900, possibly because of their complete 'black box' character.

Table 1 Advantages of the NBM-WT route relative to conventional contemporary WT-practices

No.	advantages
1	Instead of being energy demanding, they generate energy.
2	Leading to 'waste' and water recovery, i.e., waste as a valuable resource, urban agricultural practices.
3	Very low production of—well stabilized and concentrated—excess sludge.
4	Very low space requirements.
5	Low in investment, operational, and maintenance costs.
6	Simple in operation and maintenance, consequently hardly depending on specialists.
7	Use of technically simple and generally locally manufacturable equipment.
8	Long life-time of installations and auxiliary equipment.
9	Applicable at almost any scale and at almost any location.
10	Very robust, e.g., absence of any need for any complex infrastructures, e.g., for power supply.
11	Almost absence of any mal-odor nuisance problems.
12	Formation of recalcitrant organic compounds (e.g., humic acids) can be avoided.
13	Efficient in degrading various resistant compounds like azo-dyes, poly-aromatic compounds (PAC's), and nitro-aromatics.

4 Challenging expected future operational developments in NBM-based treatment

Obviously, the first priority for achieving a more sustainable EP is to accomplish the required conceptual innovations (paradigm shifts) in the sector. However, this comprises a task of immense difficulty, because the interests of the established sanitary engineering world are generally opposite, i.e., particularly directed to pursuing further technological innovations within the well established CENSA-concepts and the further world-wide implementation of these systems. However, regarding the urgent need to realize more sustainability in society, all possible emphasis needs to be put on the implementation, optimal application and the further improvement of NBM-based systems. Despite the very significant progress already made, still much more can be achieved by improving the insights in the microbiology, ecology and (bio)chemistry and reactor- and process technology of the various NMB systems. As far as AnWT/AnDi systems are concerned, numerous challenging innovations can be accomplished. This certainly is not limited to modern high rate AnWT-systems for wastewater treatment and conventional AnDi-systems for slurry stabilisation and energy production [2,45], but also for so-called “outdated” systems, like septic tanks and latrines. And as far as AnDeg-processes in the wider context are concerned, particularly the S_{biol}-cycle based systems are open for creative innovations. Regarding NBM-systems, interesting innovation undoubtedly can be expected for both high rate Ae_{micro}WT-based post-treatment systems and AeWT-based systems as well. The requirement for applying ‘post-treatment of anaerobic effluents’ is of a recent date. Furthermore, it is clear that there will evolve an increasing opportunity for nutrient recovery systems applicable for wastes, wastewaters and energy crops.

Process and operational technological improvements in AnDi and AnWT

Many improvements undoubtedly can be achieved by conducting a thorough evaluation of the enormous amount of relevant information available in literature. Unfortunately, literature search frequently receives far less priority than experimental research; it looks less prestigious. Nevertheless, still numerous issues only can be elucidated on the basis of comprehensive experimental investigations, and some of them, regarding their enormous complexity, even need a very well coordinated multidisciplinary attack over prolonged periods of time.

Below process and technological improvements in AnDi and AnWT will be discussed, viz. including operational temperature, high operational pressures, mixing conditions, occurrence of chemical precipitation, extreme salt concentrations, trace elements and macronutrients, use of electron and redox mediators, and biological sulphate reduction.

Operational temperature

The potentials of both psychrophilic and thermophilic AnDi and AnWT-systems are significant. It should be emphasized here that these systems offer the greatest potential when applied in their optimal physiological temperature ranges. However, it should be emphasized here that their application become especially useful under temperature conditions far below the optimal physiological operating temperature and, of greater importance, under varying temperature conditions as well. In this connection it should be understood that the required process-stability of AnWT-systems, when applied under whatever operational conditions, including sub-optimal, always needs careful adjustment of the imposed organic load.

The feasibility of high-rate psychrophilic EGSB-systems has been demonstrated for the treatment of volatile fatty acids containing wastewaters in bench scale experiments at temperatures down to 4°C[46]. Contrary to acidified substrates, direct application of high-rate AnWT-systems is not feasible for soluble carbohydrate wastewaters under psychrophilic conditions; a complementary acidogenic pre-treatment process step then needs to be incorporated in order to achieve the required pre-acidification [26]. However, such a complementary acidogenic reactor can probably be omitted when treating soluble protein containing wastewaters, because the yield of acidogenic sludge in that case is significantly lower than for carbohydrate substrates.

Direct application of a high rate AnWT-system under psychrophilic conditions also is not feasible for the stabilisation of insoluble organic matter; the very low rate of the hydrolysis step becomes restrictive at temperatures below 15°C–17°C High-rate AnWT-systems for treating such types of complex types of wastewaters under low ambient temperature conditions are viable only by incorporating a conventional digester, operated under optimal mesophilic temperatures, and in parallel with the high-rate reactor. The function of this complementary digester is to achieve i) a sufficient stabilization of the insoluble organic matter entrapped in the high rate reactor and ii) to enable maintenance of a satisfactory methanogenic activity in that reactor, which is accomplished by returning part of the stabilized sludge from the digester into it. This integrated UASB-AnDi-reactor concept offers promise for sewage pre-treatment under winter time conditions in moderate climate regions.

High operational pressures

So far, very little relevant information is available concerning the practical feasibility of AnDeg-systems at pressures exceeding 100 bars. However, regarding the existence of anaerobic organisms in the deep oceans, the development and implementation of ‘pressurized’ AnDi systems might offer promise, e.g., for energy generation purposes, particularly when they can be optimized by adjusting the operational temperature.

Mixing conditions

Because anaerobic organisms have a strong preference to form 'balanced' micro-ecosystems, heavy mixing in anaerobic reactors should be avoided. A gentle mode of mixing comprises a basic condition underlying the UASB-system, also of other modern high rate AnWT-reactors. However, in various earlier versions of the 'Anaerobic Contact' process, applied around the nineteen fifties and sixties for treatment of high strength industrial effluents, this condition was insufficiently met. It is probable that this also was/is not the case in many conventional sludge digesters.

Moreover, apart from enhancing process performance, the minimization of mechanical agitation will reduce the energy requirements, and thus also the investment costs.

Occurrence of chemical precipitation (e.g., $CaCO_3$, $MgNH_4PO_4$, and metal sulphides)

Chemical precipitates in and/or around immobilized films, sludge aggregates affect the performance of an AnWT quite detrimentally when during the operation of the system i) the active biomass will become scaled-in a tight $CaCO_3$-layer, ii) the sludge aggregates become far too heavy and/or iii) when it leads to 'cementing' of the sludge bed [47–51]. On the other hand, in case it is possible to control the precipitation process adequately, e.g., by maintaining the PO_4^{3-} -concentration at about 5 mg/L or by using small granules, a heavy (high ash-content) granular sludge will retain a high activity. This was demonstrated during the start-up of an 800 m^3 full scale UASB-reactor treating corn starch wastewater (COD: 1.5–11 g/L, Ca^{2+} up to 800 mg/L). It was the second full scale reactor implemented in the Netherlands, designed and commissioned according to criteria developed at our department [52]. A typical needle shaped, 60% ash-content, fine granular sludge evolved.

The benefit of a high ash-content granular sludge is that it enables the application of very high superficial velocities, e.g. as applied in EGSB-reactors [53]. It is interesting to note that this specific feature is not unique for high rate AnWT-processes, it also offers great potential for high rate upflow granular sludge Ae_{micro}-reactors for post-treatment purposes [54], very likely for high-rate granular sludge bed nitrification systems, even for granular sludge bed AeWT-systems for post-treatment, but possible even for direct treatment of sewage.

Extreme salt concentrations

Regarding the high salt content of many industrial effluents, especially in situations where water loops have been closed to a large extent, an increasing need evolves for AnWT-systems that can cope with high salt concentrations. Particularly, a need arises for AnWT-systems that can cope with high sulphate concentrations, i.e., systems capable of reducing sulphate under conditions of high salt concentrations. According to findings by Vallero et al. [55–59] the potentials of such systems are substantial.

Trace elements and macro-nutrients

Macro-nutrients (N and P) and numerous trace elements (Co, Mn, Ni, etc) are essential growth factors [60–64]. They therefore represent a unique tool for minimizing or maximizing bacterial growth, that is to say the fractional conversion of biodegradable substrate into either new biomass or methane. However, before this kind of 'steering' really can become practically fully applicable, still a lot of supplementary research needs to be done. Aspects to be elucidated with respect to the impact of trace element concern assessment of the effect of concentration, composition, mode and rate of supply, and their bio-availability, both chemical and physical. With respect to their bio-availability, the presence/absence of various types of chelating agents is of great importance.

Despite the extreme complexity of the issue of trace elements, neverless relevant information for practice has already been obtained nevertheless from laboratory investigations with respect to questions like 'Which are the really essential elements?' and 'In what amounts and how to supply them?' Based on the insights obtained, to some extent the excessive spreading of trace elements over the environment can be prevented, while concomitantly the operational cost of AnWT can be reduced. The studies conducted in our department so far particularly have been addressed to the assessment of the effect of trace elements on the anaerobic conversion of i) substrates/wastewaters originating from potato, and ii) of methanol, in the latter case both under mesophilic [65–67] and thermophilic conditions [68]. Comprehensive investigations of Florencio et al. [65–67,69] with methanol, lead to the insight that at low methanol and bicarbonate concentrations, and exceptionally low cobalt-concentration (< 0.0001 mg/L) methanogens predominate over acidogens in the methanol conversion. Methanol is converted into methane directly, not via the intermediate formation of Volatile Fatty Acid (VFA). However, acidogenesis on methanol can predominate over methanogenesis at a relatively high concentration of methanol (i.e., overloading, poor treatment efficiency), when bicarbonate is supplied to the system, when Co is available and methanogens are inhibited due to the presence of undissociated VFA (for example) or an excessively low pH in the system. Through these findings, by now a stable performance of AnWT on methanolic solutions is possible.

The extraordinary complex character of the trace element issue has been more recently elaborated in comprehensive multidisciplinary investigations by Gonzalez-Gil et al. [19]. They investigated the effect of the mode of supply of trace element cocktails and found that a continuous supply is significantly more efficient than a slug-delivered supply. Comprehensive studies of Zandvoort et al. [70–74], conducted in close cooperation with the departments of Physical & Colloid Chemistry (e.g., Jansen, Van Leeuwen, et al., [75]), revealed the detrimental effect of reduced bio-availability of the trace elements, e.g., due to their precipitation as sulphides. As remedial action the supply of chelating agents such as nitrilotriacetic acid (NTA), ethylenediaminetetraacetic acid (EDTA) and citrate were found promising; these compounds can restrict metal-sulphide precipitation, so that sufficient trace elements remain bio-available. However, it is again a very complex matter, because the chelating compound should not be easily biodegradable nor be a too strong chelating compound. Moreover, big differences in behaviour were observed between crushed and uncrushed granular sludge samples.

A category of chelating agents of eminent importance undoubtedly comprise 'humic acids'. They represent a class of natural—chemically very complex—aromatic compounds, non-biodegradable and with strong chelating characteristics. They are of extraordinary importance for life. The first time we were faced with their presence/absence in AnWT- and AnDi-experiments was with potato derived substrates/wastewaters. In digestion experiments with solid matter of potato (but without peelings) and with real potato starch wastewater conducted in UASB-pilot plants, we observed an almost 100% conversion of the substrate-COD into methane-COD. Apparently, any bacterial growth in these experiments did not occur. Bacterial growth only could be realized by supplying a trace element cocktail to the system! These observations, made in the late seventies, ultimately made the board of the Potato Starch Company decide to implement the UASB-system for the treatment of the effluents of their factories, which were for decades heavily polluting the environment. The implementation was a great success. However, looking back, it has been a delicate matter, in the sense that the success indeed depended highly on the (rough) insight obtained on the effect of presence/supply of trace elements during the previous years of research. The point in this connection is that in the preliminary laboratory experiments conducted in the early seventies with freshly prepared potato juice (i.e., in fact comprising the effluent of the potato starch industry) in AF-systems, we did not observe any need to supply a trace element cocktail, nor was any retarded bacterial growth observed.

This surprising discrepancy in behaviour between freshly prepared potato juice solutions and real potato starch wastewater may in our view be attributed to the presence of humic acids in the real wastewater and absence in freshly prepared potato juice solutions. According to Field et al. [76] humic type compounds are easily formed from the highly reduced phenolic compounds via condensation reactions under the influence of free oxygen. These phenolic compounds are present in most plant juices, especially in potato juice. In potato starch production, these compounds become exposed to air once released to the wastewater. Since they are strongly chelating agents, and are present in relatively high concentrations in many wastewaters, e.g., potato starch wastewater, they undoubtedly seriously can reduce the bio-availability of essential trace elements.

The above evidence illustrates sufficiently that clarification of the mysteries of the 'trace element matter' goes far beyond human capabilities. On the other hand, as pointed out, it is a matter of crucial importance at least to attempt to make relevant information available, even though it is very superficial.

A similar story applies for macro-nutrients such as phosphate or ammonia. The absence (or serious lack) of these macro-nutrients [77,78] will result in a severely retarded growth, although without affecting the treatment efficiency detrimentally for prolonged periods of time. However, for this category of essential nutrients few important aspects have been conclusively researched, leaving gaps in our knowledge. Compared to the issue of trace elements, it is certainly less complex.

Summarizing the above, it is evident that improving the insight into the effect of trace elements and macro-nutrients represents a matter of enormous practical impact for i) the quality of the environment, ii) for achieving an optimal performance of many biotechnological processes, and it is a matter of great scientific importance, e.g., for improving insight into natural life in general. Regarding the extraordinary complex character of this matter it implies that a lot of long-term, very well coordinated multidisciplinary research activities need to be initiated.

Use of electron and redox mediators

Compounds like humic acids, activated-carbon, quinones, e.g., anthraquinone disulfonate (AQDS), anthraquinone-2-sulphonate (AQS) catalyze the anaerobic degradation reactions of numerous recalcitrant compounds; they facilitate electron transport in the degradation of, e.g., azo dyes [79–87], and reductive de-halogenation [88]. However, as with the issue of 'trace elements' in this particular field, a better understanding is required which will lead to a wider and more optimal application of AnWT.

Biological sulphate reduction (SubioRed)

Numerous efforts have been made in the past and continue to be made in the sanitation world to suppress the occurrence of sulfate reduction (SuRed), viz. rather than attempting to take all possible benefits from it, which would be much more worthwhile. Since the late eighties numerous useful applications have already been discovered and implemented [89–92], under both mesophilic [93–97] and thermophilic conditions [58,98–101]. In several of these studies, issues such as immobilization, substrate competition between SuRed-organisms and methanogens, and exposure to high salt concentrations have been addressed.

Fascinating applications can be envisaged by combining the reductive and oxidative parts of the S_{biol}-cycle, which to some extent already have been developed and implemented. Tempting examples are the removal of sulphate from wastewater, of SO_2 from exhaust gases, of the removal and recovery of heavy metals from contaminated soils or from acid mine drain water. But still substantial optimizations can be attained, e.g. with respect to the type of electron donors to be used, applicable process conditions and the immobilization of the involved organisms.

Immobilization of anaerobic microbial consortia in granules and films comprises a phenomenon of extraordinary importance and certainly not only for high rate AnWTs. Numerous biological processes can benefit from it. Since the first observation of the sludge aggregation phenomenon in AF-experiments [102] and in UASB-experiments in the early seventies and understanding its great importance for the UASB-process [6], many researchers have attempted to elucidate the mechanism of the phenomenon, e.g., Hulshoff Pol et al. [89,103,104], McHugh et al. [5,8], Fang et al. [105], resulting in a number of 'theories'. However, to date insufficient attention has been afforded to the effect of kinetic factors such as death, decay and growth rate of organisms participating in the immobilization process. Also, a number of other important questions so far have been relatively poorly addressed, such as that of i) the mechanism of the granular sludge augmentation (increase of the volume) in AnWT-reactors, ii) how to incorporate specific organisms in an existing granular sludge in order to enable the degradation of various kinds of complex compounds, and iii) the cultivation of specific types of granular sludge by using pure cultures. Numerous challenging questions remain to be resolved; it will need well coordinated interdisciplinary research.

5 Conclusions

1) In order to attain the required sustainable protection of the environment and consequently a more sustainable society, all already available means needed for that should be disseminated without any restriction to all world citizens.

2) With the various types of available NBM-based treatment systems and complementary clean water saving methods for waste & wastewater collection and transport, the major means to attain EP_{sus} lie ready 'on the shelf'.

3) In order to accomplish the optimal application of NBM-based treatment systems there is still a lot of challenging work to be done. The efforts to be made to generate that knowledge should not remain restricted to experimental laboratory work, but particularly also should be directed to thorough evaluations of the significant amount of relevant information already available in the literature.

4) With respect to the required continued experimental research on various complex issues a much better coordinated multidisciplinary tackle should be realized over prolonged periods of time.

References

1. Brundtland Commision. Our common future—The world commission on environment and development. WCED, Oxford University Press, 1987
2. Lettinga G. A good Life environment for all. Environmental Science Engineering, 2004, 1: 77–82
3. McCarty P L. Anaerobic Waste Treatment fundamentals. Public Works, 1964, September: 107–112, October: 123–126, November : 91–94, December: 95–99
4. Wang K, Zeeman G, Lettinga G. Alteration in sewage characteristics upon aging. Water Science and Technology, 1995, 31: 191–200
5. McCarty P L. The development of anaerobic treatment and its future. Water Science & Technology, 2001, 44(8): 157–176
6. Lettinga G, van Velsen A F M, Hobma S W, de Zeeuw W J, Klapwijk A. Use of the Upflow Sludge Blanket (USB) reactor. Biotechnology Bioengineering, 1980, 22: 699–734
7. Lettinga G. Anaerobic digestion and wastewater treatment systems. A Leeuwenhoek, 1995, 67, 328
8. McHugh S, O'Reilly C, Mahony T, Colleran E, O'Flaverty V. Anerobic granular sludge bioreactor technology. Reviews in Environmental Science and Bio/Technology, 2003, 2: 225–245
9. Jewell W J, Switzenbaum M S, Morris J W. Municipal wastewater treatment with the Anaerobic attached microbial film expanded bed process. Journal WPCF, 1981, 53(4), 482–490
10. Barber W P, Stuckey D C. The use of the anaerobic baffled reactor (ABR) for wastewater treatment Review. Water Research, 1999, 33 (7): 1559–1578
11. Rittmann B, MacCarty P L. Environmental Biotechnology: Priciples and Applications, MacGraw-Hill, 2001
12. Rinzema A, A Alphenaar, G Lettinga. Anaerobic digestion of long chain fatty acids in UASB-reactors and Expanded Granular Sludge Bed reactors. Process Biochemistry, 1993, 28: 527–537
13. Rinzema A, van Veen H, Lettinga G. Anaerobic digestion of triglyceride emulsions in expanded granular sludge bed reactors with modified sludge separators. Environmental Technology, 1993, 14: 423–432
14. Rinzema A, Boone M, van Knippenberg K, Lettinga G. Bactericidal effect on long chain fatty acids in anaerobic digestion. Water Environmental Research, 1994, 66(1): 40–49
15. Hwu C S, Molenaar G, Garthoff J, van Lier J B, Lettinga G. Thermophilic high-rate anaerobic treatment of wastewater containing long-chain fatty acids: impact of reactor hydrodynamics. Biotechnology Letters, 1997, 19: 447–451
16. Hwu C S, van Beek B, van Lier J B, Lettinga G. Thermophilic high-rate anaerobic treatment of wastewater containing long-chain fatty acids: Effect of washed out biomass recirculation. Biotechnology Letters, 1997, 19: 453–456
17. Hwu C S, van Lier J B, Lettinga G. Physicochemical and biological performance of expanded granular sludge bed reactors treating long-chain fatty acids. Process Biochemistry, 1998, 33: 75–81
18. Gonzalez Gil G, Kleerebezem R, van Aelst A, Zoutberg G, Versprille A I, Lettinga G. Toxicity effects of formaldehyde on methanol degrading sludge and its anaerobic conversion in Biobed Expanded Granular Sludge Bbed (EGSB) reactors. Water Science

& Technology, 1990, 40: 195–202
19. Gonzalez-Gil, G, Kleerebezem R, Lettinga G. Formaldehyde toxicity in anaerobic systems. Water Science and Technology, 2000, 42(5–6): 223–229
20. Kortekaas S, Wijngaarde R, Klomp J W, Lettinga G, Field J A. Anaerobic treatment of hemp thermomechanical pulping wastewater. Water Research, 1998, 32: 3362–3370
21. Kato M T, Field J A, Versteeg P, Lettinga G. Feasibility of expanded granular sludge bed reactors for the anaerobic treatment of low-strength soluble wastewaters. Biotechnology Bioengineering, 1994, 44, 469–479
22. Kato M T, Field J A, Kleerebezem R, Lettinga G. Treatment of low strength wastewater in upflow anaerobic sludge blanket (UASB) reactors. Journal of Fermentation and Bioengineering, 1994, 77: 679–685
23. Rebac S, van Lier J B, Lens P, van Capellen J, Vermeulen M, Stams A J M, Dekkers F, Swinkels K Th M, Lettinga G. Psychrophilic high-rate anaerobic treatment of malting wastewater in two-module expanded granular sludge bed. Biotechnology Progress, 1998, 14: 856–864
24. Rebac S, Gerbens S, Lens P N L, van Lier J B, Stams A J M, Lettinga G. Kinetics of fatty acid degradation by psychrophilically cultivated anaerobic sludge. Bioresource Technology, 1999, 69: 241–248
25. Rebac S, van Lier J B, Lens P N L, Stams A J M, Dekkers F, Swinkels K T M, Lettinga G. Psychrophilic anaerobic treatment of low strength wastewaters. Water Science & Technolology, 1999, 39: 203–210
26. van Lier J B, Rebac S, Lens P N L, van Bijnen F, Oude Elferink S J W H, Stams A J M, Lettinga, G. Anaerobic treatment of partly acidified wastewater in a two-stage expanded granular sludge bed (EGSB) system at 8°C. Water Science & Technolology, 1997, 36: 317–324
27. Gonzalez-Gil, G, Seghezzo L, Lettinga G, Kleerebezem R. Kinetics and mass-transfer phenomena in anaerobic granular sludge. Biotechnology and Bioengineering, 2001, 73, 125–134
28. Tawlik A, Klapwijk A, Gohary F E, Lettinga G. Post-treatment of effluent of anaerobic (UASB) reactor treating domestic wastewater by a rotating biological contactor. Water Science & Technology, 2001, 45(10): 371–376
29. Tawfik A, Klapwijk A, El-Gohary F, Lettinga G. Treatment of anaerobically pre-treated domestic sewage by a rotating biological contactor. Water Research, 2002, 36(1): 147–155
30. Tawfik A, Zeeman G, Klapwijk A, Sanders W, El-Gohary F, Lettinga G. Treatment of domestic sewage in a combined UASB/RBC system, Process optimization for irrigation purposes. Water Science & Technology, 2003, 48(1): 131–138
31. Buisman C J, Lettinga G. Sulphide removal from anaerobic waste treatment effluent of a papermill. Water Research, 1990, 24(3): 313–319
32. Buisman C J, Ijspeert P, Janssen A, Lettinga G. Kinetics of chemical and biological sulphide oxidation in aqueous solutions. Water Research, 1990, 24(5): 667–671
33. Buisman C J, Drieszen W, Meyer H, Lettinga G. Effect of organic substrates on biological sulphide oxidation. Applied Microbiology and Biotechnology, 1990, 33: 459–462
34. Janssen A J H, Sleyster R, van der Kaa C, Jochemsen A, Bontsema J, Lettinga G. Biological sulphide oxidation in a fed-batch reactor. Biotechnology and Bioengineering, 1995, 47: 327–333
35. Janssen A J H, de Keizer A, van Aelst A, Fokkink R, Yangling H, Lettinga G. Surface characteristics and aggregation of microbiologically produced sulphur particles in relation to the process conditions. Colloids Surfaces B: Biointerfaces, 1996, 6: 115–129
36. Janssen A J H, Ma S C, Lens P, Lettinga G. Performance of a sulphide-oxidizing expanded-bed reactor supplied with dissolved oxygen. Biotechnology Bioengineering, 1997, 53: 32–40
37. Janssen A J H, Meijer S, Bontsema J, Lettinga G. Application of the redox potential for controlling a sulphide oxidizing bioreactor. Biotechnology Bioengineering, 1998, 60: 147–155
38. Sipma J, Janssen A J H, Hulshoff Pol L W, Lettinga G. Development of a novel Process for the Biological conversion of H_2S and Methanethiol to Elemental Sulfur. Biotechnology and Bioengineering, 2003, 82(1): 1–11
39. van den Bosch P L F, van Beusekom O C, Buisman C J N, Janssen A J H. Sulfide oxidation at halo-alkaline conditions in a fed batch bioreactor. Biotechnology and Bioengineering, 2007, 97(5) 1053–1063
40. van den Bosch P L F. Biological sulfide oxidation by natron-alakliphilic bacteris, Dissertation for the Doctor Degree. Netherlands: Wageningen University, 2008
41. van Leerdam R C. Anaerobic degradation of methanethiol in a process for liquefied petroleum gas (LPG) biodesulfurization. Dissertation for the Doctor Degree. Netherlands: Wageningen University, 2007
42. Strous M, van Gerven E, Zheng P, Kuenen J G, Jetten M S M. Ammomia removal from concentrated waste streams with the anaerobic ammoinium oxidation (ANAMMOX) process in different reaction configurations. Water Research, 1997, 31: 1955–1962
43. El-Shafai S A, El-Gohary F A, Nasr F A, van der Steen P, Gijzen H J H. Nutrient recovery from UASB effluent using duckweed. In: Proceedings 9th World Congress AD-Part 2, Antwerpen, 2001, 155–157
44. Gijzen H. Anaerobic digestion for sustainable development: A natural approach. Water Science & Technology, 2001, 45(10): 321–328
45. Chernicharo C A L, Nascimento M C P. Feasibility of a pilot-scale UASB/trickling filter system for domestic sewage treatment. Water Science & Technology, 2001, 44(4): 221–228
46. Lettinga G, Rebac S, Parshina S, Novzhevnikova A, van Lier J S, Stam A J M. High-rate anaerobic treatment of wastewater at low temperatures. Applied & Environmental Microbiology, 1999, 1696–1702
47. Batstone J D, Landelli J, Saunders A, Carrosco E F, Black L L, Keller R J. The influence of Calcium on granular sludge in a full scale UASB treating paper mill wastewater. Water Science & Technology, 2001, 45(10): 187–193
48. van Langerak E P A, Hamelers H V M, Lettinga G. Influent calcium removal by crystallization reusing anaerobic effluent alkalinity. Water Science & Technolology, 1997, 36: 341–348
49. van Langerak E P A. Control of calcium carbonate precipitation in anaerobic reactors. Dissertation for the Doctor Degree.

Netherlands: Wageningen University, 1998

50. van Langerak E P A, Beekmans M M H, Beun J J, Hamelers H V M, Lettinga G. Influence of phosphate and iron on the extent of calcium carbonate precipitation during anaerobic digestion. Journal of Chemical Technology & Biotechnology, 1999, 74: 1030–1036
51. van Langerak E P A, Ramaekers H, Wiechers J, Veeken A H M, Hamelers H V M, Lettinga G. Impact of location of $CaCO_3$ precipitation on the development of intact anaerobic sludge. Water Research, 2000, 34(2): 437–446
52. Lettinga G, Hulshoff Pol L W, Wiegant W M, de Zeeuw W J, Hobma S W, Grin P C, R ERoersma, Ayed S, van Velsen A F M. Upflow Sludge Blanket Processes. In: Proceedings 3rd Int A D Symposium, Boston, 1983, 139–158
53. van Lier J P, van der Zee F P, Tan N C G, Rebac S, Klerebezedm R. Advances in high rate anaerobic treatment: staging of reactor systems. Water Science & Technolology, 2001, 44(8): 15–25
54. Vogelaar J C T, Wal F van der, Lettinga G. A new post-treatment system for anaerobic effluents containing a high Ca^{2+} content. Biotechnology Letters, 2002, 24: 1981–1986
55. Vallero M V G, Hulshoff Pol L W, Lens P N L, Lettinga G. Effect of high salinity on the fate of methanol during the start-up of thermophilic (55°C) sulfate reducing reactors. Water Science & Technology, 2002, 45(10): 121–126
56. Vallero M V G, Hulshoff Pol L W, Lettinga G, Lens P N L. Effect of NaCl on thermophilic (55°C) methanol degradation in sulfate reducing granular sludge reactors. Water Research, 2003, 37(10): 2269–2280
57. Vallero M V G, Lettinga G, Lens P N L. Assessment of compatible solutes to overcome salinity stress in thermophilic (55°C) methanol-fed sulphate reducing granular sludge's. Water Science & Technology, 2003, 48(6): 195–202
58. Vallero M V G, Sipma J, Lettinga G, Lens P N L. High-Rate Sulfate Reduction at High Salinity in Mesophilic UASB Reactors. Biotechnology and Bioengineering, 2004, 86(2): 226–235
59. Vallero M V G, Lettinga G, Lens P N L. High rate sulfate reduction in a submerged anaerobic membrane bioreactor (SAMBaR) at high salinity. Journal of Membrane Science, 2005, 253(1–2): 217–232
60. Scherer P, Lippert H, Wolff G. Composition of the major elements and trace elements of 10 methanogenic bacteria determined by inductively coupled plasma emission spectrometry. Biological Trace Element Research, 1983, 5: 149–163
61. Speece R E, McCarty P L. Nutrient requirements and biological solids accumulation in anaerobic digestion. Advanced Water Pollution Research, 1964, 2: 305–322
62. Speece R E, Gallagher D, Parkin G F. Nickel stimulation of anaerobic digestion. Water Research, 1983, 17: 677–683
63. Speece R E. Anaerobic Biotechnology and Odor/CorrosionControl for Municipalities and Industries. Nashville: Archae Press, 2008, 405–430
64. Takashima M, Speece R E. Mineral requirements for high-rate methane fermentation of acetate at low SRT. Journal Water Pollution Control Fed, 1989, 61: 1645–1650
65. Florencio L, Jenicek P, Field J A, Lettinga G. Effect of cobalt on the anaerobic degradation of methanol. Journal of Fermentation and Bioengineering, 1993, 75(5): 368–374
66. Florencio L, Field J A, Lettinga G. The importance of cobalt for individual trophic groups in an anaerobic methanol degrading consortium. Applied and Environmental Microbiology, 1994, 60: 227–234
67. Florencio L, Field J A, Lettinga G. The role of cobalt on individual trophic groups in an anaerobic methanol degrading consortium. Applied and Environmental Microbiology, 1994, 60: 227–234
68. Paulo P L, Jiang B, Cysneiros D, Lettinga G. Effect of cobalt on the anaerobic thermophilic conversion of methanol. Biotechnology and Bioengineering, 2004, 85(4): 434–441
69. Florencio L, Field J A, Lettinga G. Substrate competition between methanogens and acetogens during the degradation of methanol in UASB reactors. Water Research, 1995, 29(3): 915–922
70. Zandvoort M H, Geerts R, Lettinga G, Lens P N L. Effect of long-term cobalt deprivation on methanol degradation in a methanogenic granular sludge bioreactor. Biotechnology Progress, 2002, 18(6): 1233–1239
71. Zandvoort M H, Osuna M B, Geerts R, Lettinga G, Lens P N L. Effect of nickel deprivation on methanol degradation in a methanogenic granular sludge bioreactor. Journal of Industrial Microbiology and Biotechnology, 2002, 29: 268–274
72. Zandvoor M H, Geerts R, Lettinga G, Lens P N L. Methanol degradation in granular sludge reactors at sub-optimal metal concentrations: role of iron, nickel and cobalt. Enzyme and Microbial Technology, 2003, 33: 190–198
73. Zandvoort M H, Gieteling J, Lettinga G, Lens P N L. Stimulation of Methanol Degradation in UASB Reactors: In situ versus pre-loading cobalt on anaerobic granular sludge. Biotechnology and Bioengineering, 2004, 87(7): 897–904
74. Zandvoort M. Trace metal dynamics in methanol fed anaerobic granular sludge bed reactors. Dissertation for the Doctor Degree. Netherlands: Wageningen University, 2005
75. Jansen S, Steffen F, Threels W F, van Leeuwen H P. Environmental Science Technology, 2005, 39(24): 9493–9499
76. Field J A, Lettinga G, Geurts M. The methanogenic toxicity and anaerobic degradability of potato starch wastewater phenolic amino acids. Biological Wastes, 1987, 21(1): 37–54
77. Alphenaar P A. Anaerobic granular sludge. Dissertation for the Doctor Degree, Netherlands: Wageningen University, 1994
78. Alphenaar P A, Sleyster R, de Reuver P, Ligthart G J, Lettinga G. Phosphorus Requirement in High Rate Anaerobic Wastewater Treatment. Water Research, 1993, 27(5): 749–756
79. Bechtold T, Burtscher E, Turccanu, A. Anthraquinones as mediators for the direct cathodic reduction of dispersed dyestuffs. Journal of Electroanalytical Chemistry, 1999, 465: 80–87
80. Cervantes F J, Dijksma W, Tuan D D, Ivanova A, Lettinga G, Field J A. Anaerobic Mineralization of Toluene by Enriched Sediments with Quinones and Humus as Terminal Electron Acceptors. Applied and Environmental Microbiology, 2001, 67(10): 4471–4478
81. Cervantes F J, van der Zee F P, Lettinga G, Field J A. Enhanced decolourisation of Acid Orange 7 in a continuous UASB reactor with quinones as redox mediators. Water Science & Technology, 2001, 44(4): 123–128
82. Cervantes F J, Duong-Dac T, Roest K, Akkermans A D L, Lettinga

G, Field J A. Enrichment and immobilization of quinone-respiring bacteria in anaerobic granular sludge. Water Science & Technology, 2003, 48(6): 9–16

83. Cervantes F J, Vu-Thi-Thu L, Lettinga G, Field J A. Quinone-respiration improves dechlorination of carbon tetrachloride by anaerobic sludge. Applied Microbiology and Biotechnology, 2004, 64(5): 702–711
84. Field J A, Cervantes F J, van der Zee F P, Lettinga G. Role of quinones in the biodegradation of priority pollutants: A review. Water Science and Technology, 2000, 42(5–6): 215–222
85. Field J A, Sierra-Alvarez R. Biodegradability of chlorinated solvents and related chlorinated compounds. Reviews in Environmental Science and Biotechnology, 2004, 3: 185–254
86. van der Zee F P, Bouwman R H M, Strik B, Lettinga G, Field J A. Application of redox mediators to accelerate the transformation of reactive azo dyes in anaerobic bioreactors. Biotechnology and Bioengineering, 2001, 75(6): 691–701
87. van der Zee F P, Lettinga G, Field J A. Azo dye decolourisation by anaerobic granular sludge. Chemosphere, 2001, 44(5): 1169–1176
88. Barkovskii A L, Adriaens P. Impact of humic constituents on microbial de-chlorination of polychlorinated dioxins. Environmental Toxicology & Chemistry, 1998, 17: 1013–1020
89. Hulshoff Pol LW, Lens P N L, Stams A J M, Lettinga G. Anaerobic treatment of sulphate-rich wastewaters. Biodegradation, 1998, 9: 213–224
90. Lens P N L, van den Bosch M C, Hulshoff Pol L W, Lettinga G. Effect of staging on volatile fatty acid degradation in a sulfidogenic granular sludge reactor. Water Research, 1998, 32: 1178–1192
91. Lens P N L, Hulshoff Pol L W, Lettinga G. Anaerobic treatment of sulfate-rich wastewaters. Recent Research Develop. Biotechnology Bioengineering, 1999, 2: 95–107
92. Lens P N L, Korthout D, Lier J B van, Hulshoff Pol L W, Lettinga G. Effect of the liquid upflow velocity on thermophilic sulphate reduction in acidifying granular sludge reactors. Environmental Technology, 2001, 22: 183–193
93. Visser A, Gao Y, Lettinga G. Effects of pH on methanogenesis and sulphate reduction in thermophilic (55°C) UASB reactors. Bioresource Technology, 1993, 44: 113–121
94. Visser A, Alphenaar P A, Gao Y, Lettinga G. Granulation and immobilisation of methanogenic and sulfate-reducing bacteria in high rate anaerobic reactors. Applied Microbiology and Biotechnology, 1993, 40: 575–580
95. Visser A, Gao Y, Lettinga G. Effects of short-term temperature increases on the mesophilic anaerobic breakdown of sulphate containing synthetic wastewater. Water Research, 1993, 27: 541–550
96. Visser A, Beeksma I, van der Zee F, Stams A J M, Lettinga G. Anaerobic degradation of volatile fatty acids at different sulphate concentrations. Applied Microbiology and Biotechnology, 1993, 40: 549–556
97. Visser A, Hulshoff Pol LW, Lettinga G. Competition of methanogenic and sulfidogenic bacteria. Water Science & Technolology, 1996, 33: 99–110
98. Rintala J, Sanz Martin J L, Lettinga G. Thermophilic anaerobic treatment of sulfate-rich pulp and paper integrate process water. Water Science & Technolology, 1991, 24(3–4), 149–137
99. van Houten R T, Yun S Y, Lettinga G. Thermophilic sulphate and sulphite reduction in lab-scale gas-lift reactors using H_2 and CO_2 as energy and carbon source. Biotechnology and Bioengineering, 1997, 55: 807–814
100. van Langerak E P A, Hamelers H V M, Lettinga G. Influent calcium removal by crystallization reusing anaerobic effluent alkalinity. Water Science & Technolology, 1997, 36: 341–348
101. Weijma J, Gubbels F, Hulshoff Pol L W, Stams A J M, Lens P N L, Lettinga G. Competition for H_2 between sulfate reducers, methanogens and homoacetogens in a gas-lift reactor. Water Science & Technology, 2002, 45(10): 75–80
102. Young J C, McCarty P L. The anaerobic filter for wastewater treatment. Journal WPCF, 1969, 41(5): 160–173
103. Hulshoff Pol L W, De Zeeuw W J, Velzeboer C T M, Lettinga G. Granulation in UASB-reactors. Water Science & Technology, 1981, 15: 291–304
104. Hulshoff Pol L W, De Zeeuw W J, Velzeboer C T M, Lettinga G. Granulation in UASB-reactors. Water Science and Technology, 1983, 15: 291–304
105. Fang H H P, Liu H. Granulation of a hydrogen-producing acidogenic sludge. In: Proceedings 9th World Congress AD-Part 2, Antwerpen, 2001, 527–532

Gatze Lettinga received his PhD in the Technical University Delft and the Inter University Reactor Institute, Delft. He joined the faculty of Wageningen Agricultural University in the Department of Environmental Technology in 1970 and rose through the ranks to Professor in Environmental Technology in 1988. Prof. Lettinga developed from the Netherlands his Upflow Anaerobic Sludge Bed Reactor system (UASB). He and his colleagues expanded the application of the system to a great variety of industrial effluents, including quite complex and even toxic wastewaters. The technology has been widely used by both industry and municipalities, since Prof. Lettinga has chosen not to patent this invention and has also shared his knowledge with young water engineers and professionals all over the world. The 2007 Tyler Prize for Environmental Achievement is awarded to him in recognition of his research and development of the environmentally sound novel process for the treatment of polluted wastewater and its implementation worldwide, especially in developing countries.