The anaerobic treatment approach towards a more sustainable and robust environmental protection

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Abstract Anaerobic biological degradation processes (AnDe), when properly integrated with complementary biological and physical methods, constitute the ideal route to a sustainable protection of the life environment. However unfortunately for a smooth implementation of AnDe-processes drastic conceptual innovations are urgently needed in the field of environment protection; the present highly centralized approach in the public sanitation sector (CENSA) need to be substituted by a concept that focuses on optimal decentralization, problem prevention, self-sufficiency, resource recovery and reuse, with coupling to agriculture practices at or nearby the location (DESAR). Although a variety of excellent DESAR-based systems already are available and anaerobic digestion and treatment methods have found successful full-scale application for waste and wastewater treatment, there still is potential to improve these systems. Interesting questions to be elucidated are the effect of trace elements and macro-nutrients, the sludge immobilization phenomenon and the effect of environmental factors like temperature, pressure, mixing. Therefore tentatively a lot of challenging interdisciplinary research is waiting to attain further profitable innovations.

Keywords Granular sludge-growth and manipulation; innovation; nutrients; paradigm; self-phasing; trace elements; valorization

Introduction
Fundamental changes are needed in society in order to attain Sustainability in the Protection of the Life Environment (SPLE) and concomitant agricultural practices. The realization of sustainability in the protection of the life environment for all people at global scale implies the elimination of extreme poverty. The moral dedication for the prosperous countries therefore is to enable people in developing countries to become self-sufficient in the protection of their own life environment at a minimum of cost, and in a really robust and sustainable way, e.g. by using updated/renovated traditional and new methods. However, since unfortunately frequently this is not in their economical interest, exactly the contrary happens, despite the clear recommendation of the Brundtland Committee (1987), who considered the extreme poverty of billions of people as one of the most serious threats to humanity. The prosperous countries continue to invest in sophisticated environmental protection concepts/systems in their countries and they implement measures which aim at realizing a utopia for the quality of the own life environment. In essence these things are highly counterproductive for making progress in improving the life environment for all people at global scale. Instead, environmental protection measures/methods should be developed and implemented, which obey the natural biological mineralization route (NBMR), which is illustrated in Figure 1. When doing so, anaerobic biological degradation (AnDeg) processes, like anaerobic digestion (AnDi) and sulphate reduction (SuRedd) would become the first major biological treatment step for the elimination of biodegradable organic matter, not Aerobic Wastewater Treatment (AeWT) but Anaerobic Wastewater Treatment (AnWT) processes, as proposed in the nineteen-sixties by McCarty (1964) and Young & MacCarty (1969). The (micro-)aerobic steps, although still essential, are complementary to AnWT, they mainly serve to achieve
an optimal life environment (LE) for oxygen-respiring higher organisms. By applying NBMR in waste and wastewater treatment all essential ingredients for future life are made available in an extremely efficient way, while at the same time it can help us to valorize wastes and residues, because the NBMR-based technologies are plain and robust and they meet in essence all criteria for sustainability (see Table 1).

**Towards sustainable life environment protection and agriculture at global scale**

AnDeg-systems are extremely efficient in a) stabilizing biodegradable organic matter, consequently as a pre-treatment method for wastewaters etc, b) the generation of an energy carriers like CH₄ (van Haandel *et al.*, 1993) and possibly H₂ (e.g. Hawkes *et al.*, 2001) or even the direct generation of electricity, c) making available of nutrients (fertilizers) and elementary sulfur and d) producing valuable organic soil conditioners.

**The present application of AnDi- and AnWT processes**

In the public sanitation (PuSan) sector AeWT became the main secondary treatment system, leaving for AnDeg-processes the role for stabilization of primary and secondary sludges! Despite the big promises of the first AnWT-systems used in around 1900 little work has been done to improve this technology, quite contrary to AeWT-technology. Practice learns that it is extremely difficult to substitute a well established technology for an alternative, even when this is much more sustainable and profitable for society. Frequently decisions are made on rather obscure grounds and not in the benefit of the citizens. A very recent example is the decision to construct a huge AeWT plant for the treatment of more than 200,000 m³/day sewage of the city of Amman, despite the fact that the decision makers were well aware that AnWT is very well feasible for pre-treatment and by far the most economical and sustainable solution for the country. Similar sad developments are seen elsewhere, not in the benefit of the people but of business. Nevertheless, the position of AnWT gradually becomes stronger, especially in the industrial sanitation sector. A large number of one-step high rate AnWT-installations has been successfully installed for the treatment of a large variety of industrial wastewaters (Lettinga, 1996), and fortunately, this increasingly happens for the treatment of sewage in tropical countries (Lettinga, 2001), such as India (*Khan et al.*, 2001) and Brazil.

**Table 1 Essential criteria for sustainable environmental protection**

- Pollution prevention by minimizing the generation of wastes and wastewaters
- Use of efficient collection and treatment concepts, which don’t consume energy and resources
- Valorization of waste(water)s, preferentially at or nearby the location
- High extent of robustness and self-sufficiency
(Chernicharo et al., 2001a, Foresti, 2001). Apart from their generally satisfactory performance and economical profitability, it also is increasingly understood that they offer extraordinary potentials for closing of water and substance cycles at the site or in the region. The latter can lead to various types of new agricultural practices. Important achievements during the last decades in the process and reactor technology of AnWT-processes comprise:

- Development of a variety of low cost ‘one-step high rate’ reactor systems, such as UASB and EGSB, stationary or mobile upflow and down-flow Anaerobic Filter (AF) and Attached Film Expanded Bed (AFEB) reactors, hybrid reactors and Sequential Batch Reactors (SBR).
- Successful application of AnWT, and to some extent of SuRed-processes, under mesophilic conditions, but gradually also under psychrophilic and thermophilic conditions.
- Improved insight in to the process technology, in bacterial immobilisation, and in the integration of the different types of AnDeg-processes and in measurement and control strategies.

Moreover, substantial progress also has been made in the NBMR polishing steps, such as:

- Micro-aerobic treatment systems for i) the conversion of volatile organic and inorganic S-compounds into elementary sulfur (e.g. Sipma et al., 2001), ii) the removal remaining biodegradable dissolved organic matter and colloidal organic matter, including pathogenic organisms (Tawfik et al., 2001).
- The development of new and/or adoption of conventional AeWT-systems (Pynaert et al., 2001).
- The application of physical–chemical methods for removal and recovery of nutrients, such as stripping, scrubbing, ion exchange and chemical precipitation.

**Urgency for conceptual and or technological innovations**

**Substitution of outdated paradigms/concepts**

The industrialised world eagerly hunts for technological breakthroughs, unfortunately not particularly for improving the quality of life, but mainly for accomplishing an on-going economical growth. They generally deal with technological innovations within well established structures, such as those within the PuSan sector. However, society needs conceptual innovations, which lead to the substitution of extremely Centralised Sanitation concepts (CENSA) presently in use in the public sector (Niemczynowicz, 2001).

The paradigm of “big scale transport” should be abandoned and the uses of AeWT as secondary main treatment step as well, irrespective if they comprise high-tech compact or ‘so-called’ low-cost extensive systems (lagoons and wetlands). The implementation of CENSA systems leads to postponement of the implementation of the adequate NBMR systems. Fortunately developing countries like India, Colombia, Brazil and Mexico already started the implementation of AnWT for sewage treatment, despite the strong reluctance of the established PuSan-world (Chernicharo, et al., 2001b). And elsewhere the insight is slowly growing that in essence there don’t exist comprehensive arguments to postpone the implementation of modern AnWT systems in sewered cities. It will make the CENSA approach a bit sustainable and more robust; but it is just a first step on a long way, because most of the other non-sustainability drawbacks of CENSA remain. In order to proceed towards the utopia of a good life environment for all people, a number of new paradigms need to be accepted, viz:

- Putting the highest priority to prevention of pollution problems.
- Keeping wastewater(s) as concentrated as possible.
Minimization of use of energy and resources in the collection, transport and treatment. It would be good if these paradigms also could be accepted in the modern ‘industrialised type of agriculture’, which is so severely directed on large scale farming and international transport (even increasingly global) and on high productivity. It looks extremely difficult to make this type of agriculture sustainable.

The established CENSA world frequently is quite negative and sceptical with respect to the concept of DESAR₃, (e.g. Harremoes, 1997). But the benefits and potentials are so big (e.g. Wilderer, 2001, Zeeman et al., 2000, 2001), that this concept irrevocably will find its way, despite the fact that still numerous optimizations can achieved, such as the development of proper a) systems for the separate collection of domestic waste(water)s and residues, b) community on-site transport and storage systems, and c) specific post-treatment systems. Excellent AnWT and AnDi systems are already available for pre-treatment of more concentrated wastewaters and (semi) solid wastes, but some of the ‘old’ systems can be updated substantially. Moreover, excellent AeWT systems are available for the treatment of very low strength wastewaters and for the polishing of anaerobic effluents; but also here improvements can be realised. The main problems in DESAR₃ concern the economical removal and recovery of nutrients: the concept pursues for an integration of food production with living, consequently for urban agriculture.

Innovations of processes and reactor systems

Any further emphasis on further technological innovations within the established CENSA concept should be omitted, because they only will lead to marginal further improvements of (surface water) quality of the environment, to capital destruction. They hardly contribute to savings in the consumption of energy and resources. On the other hand within the NBMR concepts a variety of useful innovations can be realized, both in the process and reactor technology. So for instance the so-called “outdated” systems, like septic tanks and latrines can be substantially improved with relatively simple means; the same is true for modern high rate AnWT systems as secondary (pre-)treatment method for sewage and for conventional AnDi systems for slurry stabilisation en energy production. The application of Sbiol-cycle processes is of recent date and consequently is open for substantial improvements, like the application of high rate micro-aerobic and aerobic post-treatment systems. So far, the initiatives to change the situation with respect to the position of these methods mainly came from universities; we may expect more initiatives for realising innovations from the industry and the governmental organisations in near future, not merely for their use in waste(water) treatment, but also for the generation of (bio)energy (van Haandel and Lettinga, 1993, Van Haandel 2001) and likely for nutrient recovery from wastes, wastewaters and energy crops.

Process technological improvements in AnDi and AnWT

Operational temperature. Although so far not widely used, the potentials for application of psychrophilic and thermophilic AnDi and AnWT systems are enormous, including their use far below their optimal temperatures and fluctuating temperatures. Psychrophilic AnWT represents a very feasible and attractive option for the treatment of soluble acidified wastewaters (Rebac et al., 2001), but much less for the stabilisation of insoluble complex organic wastes. Under low temperature conditions the rate of the hydrolysis step becomes too low. Latter problem can be overcome by combining a high rate psychrophilic AnWT reactor with a conventional digester, operated in the optimal mesophilic temperature range. By returning stabilized sludge from this digester to the AnWT reactor (Mahmoud, et al., 2004) the quality of the sludge in the high rate
AnWT reactor can be maintained at a sufficiently high level to enable the system satisfactory COD efficiencies with sewage at ambient temperatures below 13°C.

Operational pressure. Hardly any relevant information is available about the possibilities to apply AnDeg systems at high pressures, e.g. exceeding 100 bar, but likely the process then still proceeds satisfactory. High pressure AnDi might become attractive for practice, provided the costs of the reactors are reasonable, e.g. for energy generation purposes, particularly when the process can be optimized by adjusting the operational temperature.

Mixing conditions. Since anaerobic organisms prefer to live in ‘balanced’ micro-ecosystems (mechanical) mixing in an anaerobic reactor always should be kept at a minimum (e.g. Angement et al., 2001), a condition which is perfectly met in all modern high rate AnWT reactors, but likely insufficiently in sludge (slurry) digesters. Apart from a better process performance, minimization of mechanical agitation will result in a reduction of the lower energy requirements.

The occurrence of chemical precipitations (e.g. of CaCO₃) in and/or around sludge aggregates can affect the performance of an AnWT quite detrimentally in case the active biomass would become completely scaled in, or when far too heavy aggregates are formed (e.g. Langerak et al., 1997,1999, Batstone et al., 2001). However, when salt precipitation can be sufficiently controlled it enables the application of upflow (anaerobic) reactors (e.g. Van Lier and Boncz 2001) or (micro)aerobic upflow reactors under extremely high liquid upflow velocities.

Trace elements and macro nutrients are essential growth factors (e.g. Scherer et al., 1983, Speece et al., 1964, 1983, 1986, Takashima and Speece 1989) offering operators/engineers unique possibilities for process optimization. When present in sufficient amount and composition, and in the proper chemical form — either from origin or supplied — growth of the relevant organisms will be optimal. However, when this condition is not met, as for instance observed in our laboratory in UASB-start-up experiments with potato starch wastewater and in digestion experiments with dry solids of potato — both in fact a ‘rich’ complex substrate — growth hardly occurred. Instead we noticed in the digestion of the dry potato solids an auspicious and almost complete conversion of the substrate COD into methane-COD, consequently a complete conversion of organic biomass into energy. However for accomplishing a satisfactory sludge granulation on potato waste-water the supply of a cocktail of trace elements is a prerequisite. The enormous effect of trace elements also has been demonstrated in comprehensive investigations with methanol as substrate in our laboratory (Florencio et al., 1994, Paulo et al., 2001). Here Co appeared to be the essential element. In 2001 funding was received to continue these investigations in a big joint project between researchers in the disciplines of environmental technology, microbiology and physical chemistry, dealing with various of the aspects of this fascinating matter. With this joint activity already considerable progress has been made with respect to the anaerobic degradation of methanol. But there are a lot more substrates!

As far as macro-nutrients concerned, very similar observations made, e.g. for the effect of phosphate (Alphenaar, 1993, 1994). Considering the state of art of this matter, we must conclude that still a lot is ‘obscure’, particularly for the effect of trace elements. Regarding its big practical and scientific importance, it is surprising how little attention has been paid to this matter so far. It is highly needed to change the situation, the more...
so because within a relatively short period of time undoubtedly very significant progress can be made, at least when the research can be organised in long-term interdisciplinary projects.

*Use of electron and redox mediators*, such as humic acids and quinone model compounds, e.g. anthraquinone disulfonate (AQDS), likely will lead to a much wider application of AnWT, because these compounds catalyse the anaerobic degradation of numerous recalcitrant compounds, e.g. azo dyes (Field, 2001).

*Self-phasing ability of AnDi and AnWT systems*. Modulated reactor systems, provided they are properly designed and operated, enable the growth of specific types of bacterial consortia in each of the separate modules. In fact a smooth natural type of sludge segregation occurs over the modules. Therefore (contrary to the operation of the conventional anaerobic baffled reactor, ABR) mixing up of the sludge over the modules should be avoided (Bell et al., 2001), while in addition, each module also needs its own gas atmosphere (Lettinga, 1995). Compared to one-step reactors the staged reactors AnWT systems provide substantially higher removal efficiencies, particularly for ‘difficult’ compounds. Moreover, their applicable loading potentials are substantially higher than of the ‘one-step’ AnWT reactor. The process of self-phasing presumably can proceed for all bacterial groups involved in the degradation processes, including sulphate reducers. However a complete separation of the various conversion steps, e.g. of methanogenesis and sulphate reduction, likely is not possible.

*Sulphate reduction (SuRed)*. The last decades brought the insight that a profitable use can be made of the process of SuRed, rather than trying to suppress it. This insight already led to numerous very useful applications, such as in wastewater treatment for the removal of sulfate, in exhaust gas treatment for the removal of SO$_2$ and in soil remediation for the removal and recovery of heavy metals. But undoubtedly still a lot can be improved, such as with respect to choice of electron donors, the process conditions, the immobilization of the organisms.

*Immobilisation of anaerobic microbial consortia in granules and films*. The fascinating phenomenon of granular sludge, observed for the first time by Young and McCarty (1969) in the sixties in AF-systems, challenged many researchers to elucidate the underlying mechanism, e.g. Fang et al., (1994), Fang and Liu (2001), Hulshoff Pol et al., (1983, 2002). This resulted in a variety of ‘theories’ on the granular sludge formation phenomenon. However so far a number of other important questions were hardly addressed (Lettinga, 1995; Lettinga and Hulshoff Pol, 2002), viz:

- the mechanism of the granular sludge augmentation (growth of the amount) in AnWT-reactors,
- how to incorporate specific organisms in an existing granular sludge to enable the degradation of various kinds of complex compounds.
- the possibilities to cultivate a specific granular sludge by using pure cultures.

In the various granular sludge formation theories, surprisingly little if any attention has been given to the effect of kinetical factors such death, decay and growth rate of various organisms. Regarding the present situation it is obvious that still a lot of challenging interdisciplinary research is waiting to elucidate all these questions. Below follow some suggestions.
The augmentation process of mature granules. A prerequisite for the stable operation of EGSB reactors it that sludge granules should not 1) fall apart into very small fragments, because the retention of small fragments is very difficult, 2) grow too big, because then the bacterial consortia in the core might remain deprived from substrate, which clearly limits the specific loading potentials of the sludge and may lead to death and decay of organisms, possibly followed by a serious disintegration of the grains. Moreover buoying of the grains will be greatly enhanced as observed for an EGSB reactor treating brewery wastewater by Gonzalez et al. (2001) and Takeda et al. (2001). Latter problem can be overcome by grinding the grains! Contrary to the views of Pereboom (1994), we consider the occasional (once in a period of several months) breaking up of the big mature granules into a limited number of fragments as the predominate mechanism controlling the size of the granular sludge in an anaerobic reactor. This breaking up process presumably depends strongly on the reactor type, i.e. will be different in a USAB, EGSB, or the “Fluidized Bed” reactor investigated by Iza (1991) and the AFFEB-rector of Jewell et al. (1981). The size of the fragments will increase through growth of the organisms present in the grain, likely also through agglomeration (Binot et al., 1983). In earlier investigations (Hulshoff Pol et al., 1983) we observed the strong stimulating effect of the supply of ‘crushed granular sludge’ on sludge granulation. The maximum size of the granules depends on the intrinsic strength of the aggregates and on ‘external and internal’ forces exerted on the particles/films, particularly the short-term fluctuating liquid and gas pressures to which they are exposed in the reactor system. It is clear that bacterial growth should proceed throughout the mature dense aggregate; consequently substrate needs to penetrate down to the grain core by diffusion and convection (Kato et al., 1999). In view of the high bacterial density, the ‘in-growing’ organisms need to make space available in the grain. Latter only can proceed via the formation of new cracks, splits and cavities, a process presumably greatly stimulated by the gas bubble(s) formation inside the grain. A lot is obscure about questions as: “When, where and how gas bubbles appear?” and “How and where they are released?” However, it is likely rather violent forces prevail inside the grains, since a) an amount of 4–5 times the granule volume per hour can be produced at an imposed sludge load of 1 kg COD/kg VSS/day, b) the grains are exposed to short-term fluctuating pressures in an upflow reactor; they raise and settle over the height of the reactor within a few seconds. The latter depends on the structure of granules, the imposed load, the dynamics of reactor, i.e. the extent of vertical and horizontal mixing.

The manipulation of existing granules. Excess granular sludge represents an excellent seed material for the start-up of new reactors, even when these treat a rather different wastewater. However the start-up should be made cautiously. The situation becomes more complex when the new wastewater is highly different in composition, strength, salinity (Vallero et al., 2003) and temperatures (e.g Paulo et al., 2001). Then serious problems may manifest, such as a) deterioration of the granules through attachment of fast growing filamentous acidogenic bacteria, b) buoying of the granules due to formation of scaled structures within the grain (Alphenaar, 1994), c) CaCO3-scaling (Langerak, 1999) and d) incomplete degradation of polluting substances due to lack of the required specific organisms in the consortium. Contrary to partially acidified sucrose wastewater, few if any problems have been found with non-acidified gelatine wastewaters (Alphenaar, 1994). The rapid growth-in of the rather filamentous acidogenic organisms (high growth yield) becomes more problematic at lower temperatures, because the death (and decay) of these organisms then is very low compared to higher temperatures. The major part of the ingrown acidogens will disappear soon under mesophilic conditions, because of their
high death and decay rates and the high sludge ages of these systems. But this is not the case under psychrophilic conditions, viz. somewhere below 15°C. It illustrates the importance of adequate knowledge of the kinetic parameters of the various types of organisms involved in anaerobic sludge immobilisation.

An important question is how to incorporate a new specific organism required for the degradation of specific compounds present in a new type of wastewater within the dense structures of an existing granular sludge (or film). Since freely dispersed organisms present (e.g. supplied) in the external solution only can penetrate in an existing granular via cracks, it is clear that their incorporation in an existing granular sludge is problematic. (Kleerebezem, 1999; Hwu et al. (1997). The best in that case procedure likely is to start the system with ‘well’ crushed granular sludge.

Cultivation of granules using defined (pure) cultures. An interesting and challenging possibility to cultivate specific granules composed of unique micro-ecosystems might represent the use of selected cocktails of pure cultures.

Potential reactor technological improvements

The AnDi and AnWT processes

Regarding the availability of a variety of well functioning high-rate AnWT reactor systems, the need for innovative systems looks small, at least not for the reason to save space or to improve the retention of sludge. Certainly an important place is left for ‘ordinary’ stirred anaerobic stirred tank reactor, provided mixing is made intermittently (Lettinga 1995). These systems can use both a granular sludge as well as a dense well settling flocculent type of sludge. There might also exist a niche for developing an anaerobic MBR e.g. for those situations where specific essential organisms can not be immobilised in aggregates or films. But as explained above, likely well designed and operated moduled reactors systems offer great perspectives (van Lier et al, 1994).

For the treatment of ‘cold’ (temperatures below 10–14°C) non-acidified soluble carbohydrate wastewaters it might become interesting to develop a stable high rate acidogenic reactor. Due to the low death and decay rate of acidogenic organisms at low temperatures, the performance of a one step UASB-reactor is unsatisfactory.

The micro-aerobic and aerobic polishing processes

Numerous innovations likely can be realized for the oxygen demanding polishing steps of NBMR, although already considerable progress has been during the last two decades with micro-aerobic systems. This applies particularly for the oxidative part of $S_{\text{biol-cycle}}$, i.e. with the biological conversion of sulphide into elementary sulphur (Buisman et al., 1989). This process is extremely attractive for $H_2S$ removal from biogas and natural gas, and likely also for the removal of other volatile organic S-compounds (e.g. mercaptans, disulphides) from air or aqueous solutions.

New high rate (micro-) aerobic reactors/processes likely can be developed for the removal of colloidal matter, dispersed organisms (e.g. pathogens) and part of remaining soluble COD from anaerobic effluents. This also may the case for ammonia removal.

Final discussion and conclusions

The major challenge of human society undoubtedly is to realize a clean healthy life environment for all people. Most of the required tools already are available with various traditional and modern treatment systems based on NBMR, such as the various AnDe processes as first treatment step, i.e. AnWT and AnDi systems, including also processes based on $S_{\text{biol-cycle}}$. The main difficulty in the implementation of these systems lies in
the hopeless rigidity of established structures, e.g. those who want to continue the use of treatment systems based on highly non-sustainable paradigms of large-scale transport and the use of AeWT systems as first treatment step. These paradigms need to be substituted by new ones, which focus on problem prevention, decentralization, self-sufficiency and waste valorization, consequently the use of DESAR3-concept. Despite all the progress made the last decades in the field of AnDe-systems and polishing methods as well, still an abundance of fascinating fundamental and technology-oriented research remains to be done. Substantial progress can be made, although it likely needs much more long-term inter-disciplinary and inter-university joint research than is so far the case. We need research globalization, although … we should not forget this, available NBMR-based systems already now can be profitably applied; therefore their implementation should not be postponed. And above all, priority should be given to the development of urban agriculture, so instead of urbanization we should attempt ruralization.

We need an holistic approach, no monopolization of activities by ‘top specialists and scientists’, but participation of all people, so that they will get more time for spiritual and intellectual development… and enjoyment. The best renewable resource is mankind.

References


