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Solid waste digestors: process performance and practice for municipal solid waste digestion

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Abstract The most common types of anaerobic digesters for solid wastes have been compared based on biological and technical performance and reliability. Batch systems have the most simple designs and are the least expensive solid waste digesters. They have high potential for application in developing countries. Two-stage systems are the most complex and most expensive systems. Their greatest advantage lies in the equalisation of the organic loading rate in the first stage, allowing a more constant feeding rate of the methanogenic second stage. Two-stage systems with biomass accumulation devices in the second stage display a larger resistance toward toxicants and inhibiting substances such as ammonia. However, the large majority of industrial applications use one-stage systems and these are evenly split between “dry” systems (wastes are digested as received) and “wet” systems (wastes are slurried to about 12% total solids). Regarding biological performance, this study compares the different digester systems in terms of organic loading rates and biogas yields considering differences in input waste composition. As a whole, “dry” designs have proven reliable due to their higher biomass concentration, controlled feeding and spatial niches. Moreover, from a technical viewpoint the “dry” systems are more robust and flexible than “wet” systems.

Keywords Biogas yield, biological performance, grey waste, inhibition, OFMSW, organic loading rate, total solids

Introduction

The discussion and evaluation of reactor designs generally depends on biological, technical, environmental and last but not least, economical aspects. This paper strives to address the technical and biological viewpoints in depth and highlights a few environmental and financial issues.

The scope of this paper is limited to feedstocks consisting mainly in the organic fraction of municipal solid wastes (OFMSW) sorted mechanically in central plants or organics separated at the source, referred to here as biowaste (the vegetable-fruit-garden, or VFG, fraction). Necessary pre-treatment steps may include magnetic separation, comminution in a rotating drum or shredder, screening, pulping, gravity separation (dry separation) or pasteurization (Figure 1). As post-treatment steps, the typical sequence involves mechanical dewatering, aerobic maturation, and water treatment but possible alternatives exist such as biological dewatering or wet mechanical separation schemes wherein various products may be recovered.

The two main parameters chosen to classify the realm of reactor designs are the number of stages and the concentration of total solids (% TS) in the fermenter because these parameters have a great impact on the cost, performance and reliability of the digestion process. Of each of the discussed reactor systems, a short general theoretical approach will be given. Subsequently, practical considerations will be made with respect to reactor performance and compared with expected results from the literature.

Finally, future perspectives for the digestion of OFMSW are given and the role of solid waste digestion in integrating treatment technologies for grey household waste is formulated.

One-stage systems

The biomethanization of organic wastes is accomplished by a series of biochemical transformations, which can be roughly separated into a first step where hydrolysis, acidification and liquefaction take place and a second step where acetate, hydrogen and carbon dioxide are transformed into methane. In one-stage systems, all these reactions take place simultaneously in a single reactor, while in two- or multi-stage systems, the reactions take place sequentially in at least two reactors.

About 90% of the full-scale plants currently in use in Europe for anaerobic digestion of OFMSW and biowastes rely on one-stage systems, approximately evenly split between "wet" and "dry" operating conditions (De Baere, 2000). This is probably due to the lower cost of one-stage systems compared to two-stage systems.

One-stage "wet" complete mix systems

Technical evaluation. Under the term "solid waste", one generally understands organic biodegradable waste with more than 15% TS. In "wet" complete mix systems the organic solid waste is diluted with water via pulping and slurrying to less than 15%TS. Consequently, digesters of the CSTR-type (completely stirred tank reactor) are mostly used in this type of application.

One of the first full-scale plants for the treatment of biowastes, built in the city of Waasa, Finland, in 1989, is based on this principle (Figure 2).

A pulper with three vertical auger mixers is used to shred, homogenize and dilute the wastes in sequential batches. To this end, both fresh and recycled process water are added to attain 10–15% TS. The obtained slurry is then digested in large complete mix reactors where the solids are kept in suspension by vertical impellers.

Many technical aspects need actually be taken into account and solved in order to guarantee a satisfactory process performance (Westergard and Teir, 1999; Farneti *et al.*, 1999). First of all, one should realise that the origin and kind (composition) of organic solid waste has a significant influence on biodegradability and consequently on biogas yields. For instance, mechanically sorted OFMSW has a very different biodegradability compared to source-sorted OFMSW (the latter has a higher digestability). For both mechanically sorted

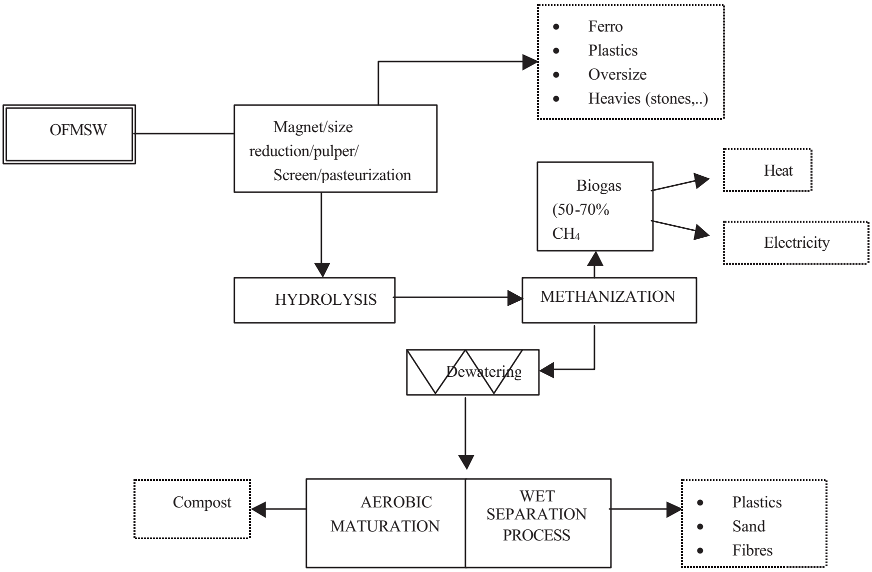

Figure 1 Overview of possible pre- and posttreatment technologies in OFMSW digestion

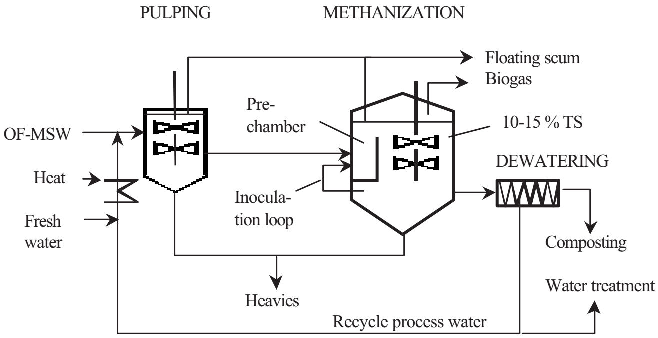

Figure 2 Typical design of a one-stage "wet" system

OFMSW and source-sorted OFMSW, the selective removal of coarse contaminants from the mainstream can be difficult to achieve. Therefore, a complicated plant is required involving the use of screens, pulpers, drums, presses, breakers, and flotation units. These pre-treatment steps inevitably result in a 15–25% loss of volatile solids, with a consequent proportional drop in biogas yield (Farneti *et al.*, 1999).

Secondly, slurried wastes do not always keep a homogenous consistency because on the one hand heavier fractions and contaminants might sink and on the other hand a floating scum layer forms during the digestion process due to foam producing substances present in plant materials. This results in the formation of three layers of distinct densities, or phases, in the reactor. The heavy particles accumulate at the bottom of the reactor and may damage the propellers while the floating layer, several metres thick, accumulates at the top of the reactor and will hamper effective mixing. It is therefore necessary to foresee means to extract periodically the light and heavy fractions from the reactor. Since the heavy particles also damage pumps, they must be removed as much as possible before they enter the reactor, either in specifically designed hydrocyclones or in the pulper which is designed with a settling zone.

A final technical drawback of the complete mix reactor is the occurrence of short-circuiting, i.e. the passage of a fraction of the feed through the reactor with a shorter retention time than the average retention time of the bulk stream. This generally results in a decreased biogas production and less kill-off of microbial pathogens.

Biological performance. A useful tool for characterisation of biological performance is the maximum sustainable reaction rate, which can be expressed as a rate of substrate addition, i.e. the maximum organic loading rate (OLR_{max} expressed in kg VS/m^3 reactor.d), or as a rate of product formation, i.e. the volume of dry biogas or, better, of methane (under standard conditions of pressure and temperature) produced per unit time per unit reactor volume (m^3 CH_4/m^3 reactor.d). Another parameter of use to quantify the rate is the retention time, which is roughly the inverse of the OLR when the OLR is expressed as mass wet substrate instead of mass substrate VS. The best way to compare the biological performance of different reactor designs requires however the use of all three indicators simultaneously. The OLR_{max} indicates the degradative capacity of the system and the biogas yield its conversion efficiency, with 100% conversion efficiency being defined as the maximum biogas yield potential determined under optimal conditions in the laboratory. If the OLR_{max} is unknown, the biogas yield still remains a valid indicator for comparisons between studies where only wastes of similar origin and composition are used. Effectively, biogas yield in solid waste digestion as such is much more dependent on waste composition than on process performance.

Typical OLR_{max} values for one-stage "wet" digestion of OFMSW are in the range of 5–10 kg VS/m^3.d. These values are particularly dependent on the origin and composition of the biowaste. As a whole, the pulping of the solid waste results in a better hydrolysis and homogenisation of the waste (Stroot *et al.*, 2001). Consequently, one may expect higher biogas yields applying one-stage "wet" digestion in comparison with one-stage "dry" digestion since bacteria have better access to the substrate. However, the technical drawbacks (loss of biodegradable material when removing coarse materials, scum layer and heavies) overcompensate this effect resulting in a similar or even lower biogas yield compared to one-stage "dry" systems for the same solid waste feed.

Economical and environmental issues. The slurrying of the solid wastes brings the economical advantage that cheaper equipment may be used, e.g. pumps and piping, relative to solid materials. This advantage is however balanced by the higher investment costs resulting from larger reactors with internal mixing, larger dewatering equipment, and necessary pre- and post-treatment steps. Overall, investment costs are comparable to those for one-stage "dry" systems.

One drawback of ecological and economical significance is the incomplete biogas recovery due to the loss of biodegradable organics with the removal of the floating scum layer and the heavy fraction. Another one is the relatively high water consumption necessary to dilute the wastes (about 1 m^3 tap water per ton solid waste).

One-stage "dry" systems

Research during the 80's demonstrated that biogas yield and production rate were at least as high in systems where the wastes were kept in their original solid state, i.e. not diluted with water (Spendlin and Stegmann, 1988; Baeten and Verstraete, 1993; Oleszkiewicz and Poggi-Varaldo, 1997). The challenge in this technique was not one of keeping biochemical reactions going at high TS values but of handling, pumping and mixing solid streams. The new plants erected during the last decade are evenly split between the wet and the dry systems (De Baere, 2000).

*Technical evaluation. I*n dry systems, the fermenting mass within the reactor is kept at a solids content in the range 20–40% TS. Consequently, only very dry substrates (> 60% TS) need to be diluted with process water (Oleszkiewicz and Poggi-Varaldo, 1997). The physical characteristics of the wastes at such high solids content impose technical approaches in terms of handling, mixing and pre-treatment which are fundamentally different from those of wet systems.

Transport and handling of the wastes is carried out with conveyor belts, screws, and powerful pumps especially designed for highly viscous streams. This type of equipment is more expensive than the centrifugal pumps used in wet systems. However, this equipment is much more robust and flexible since wastes with solid contents between 20 and 50% can be handled and impurities such as stones, glass or wood do not cause any hindrance. The only pre-treatment which is necessary before feeding the wastes into the reactor is the removal of the coarse impurities larger than ca. 40 mm. This makes the pre-treatment of dry systems somewhat simpler than that of their wet counterparts and very attractive for the biomethanization of OFMSW which typically contain 25% by weight of heavy inerts.

Due to their high viscosity, the fermenting wastes move via plug flow inside the reactors, which offers the advantage of technical simplicity as no mechanical devices need to be installed within the reactor. At least three designs have been demonstrated effective for the adequate mixing of solid wastes at industrial scale (Figure 3).

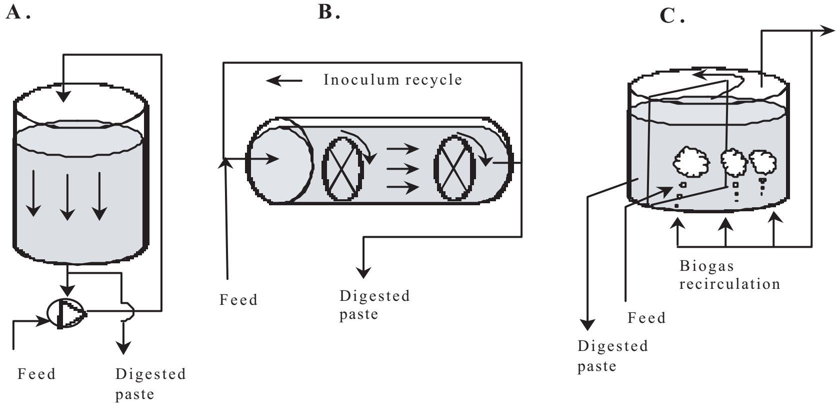

Figure 3 Different digester designs used in "dry" systems (A illustrates the Dranco design, B the Kompogas and BRV designs, and C the Valorga design)

In the Dranco process, the mixing occurs via recirculation of the wastes extracted at the bottom end, mixing with fresh wastes (one part of fresh waste for six parts of digested waste), and pumping to the top of the reactor. This simple design has been shown effective for the treatment of wastes ranging from 20 to 50% TS.

The Kompogas process works similarly, except that the plug flow takes place horizontally in cylindrical reactors. The horizontal plug flow is aided by slowly rotating impellers inside the reactors, which also serve for homogenization, degassing, and resuspending heavier particles. This system requires careful adjustment of the solid content around 23% TS inside the reactor. At lower values, heavy particles such as sand and glass tend to sink and accumulate inside the reactor while higher TS values cause excessive resistance to the flow.

The Valorga system is quite different in that the horizontal plug flow is circular in a cylindrical reactor and mixing occurs via biogas injection at high pressure at the bottom of the reactor. This biogas injection takes place every 15 minutes through a network of injectors (Fruteau de Laclos *et al.*, 1997). Due to mechanical constraints, the volume of the Kompogas reactor is fixed and the capacity of the plant is adjusted by building several reactors in parallel, each one with a treatment capacity of either 15,000 or 25,000 ton/yr (Thurm and Schmid, 1999). Possible drawbacks of this system are the clogging of the gas injection ports and the overall maintenance.

Biological performance. In terms of extent of VS destruction, the three "dry" reactor designs discussed above seem to perform very similarly, with biogas yields ranging from 90 m^3/ton fresh garden waste to 150 m^3/ton fresh food waste (Fruteau de Laclos *et al.*, 1997; De Baere, 2000). These yields correspond to 210–300 m^3 CH_4/ton VS, i.e. 50–70% VS destruction.

Differences among the dry systems are more significant in terms of sustainable OLR. The Valorga plant at Tilburg, The Netherlands, treats waste peaks of 1,000 ton VFG wastes per week in two digesters of 3,000 m^3 each at 40°C (Fruteau de Laclos *et al.*, 1997). This corresponds to an OLR of 5 kg VS/m^3.d, a value comparable to the design values of plants relying on wet systems. Optimized "dry" systems may however sustain much higher OLR such as the Dranco plant in Brecht, Belgium, where OLR values of 15 kg VS/m^3.d were maintained as an average during a one-year period (De Baere, 2000).

When comparing "dry" and "wet" one-stage systems in terms of biological performance, OLR_{max} and biogas production need to be considered simultaneously. In the digestion of OFMSW, the OLR_{max} will be largely determined by the growth rate of the acid producing and hydrolyzing bacteria and the growth rate of the methanogenic bacteria. This is particularly true for the VFG-fraction which generally has a very high biodegradability resulting in high acid production and high biogas yields.

As a whole, higher OLR are being achieved in both bench scale and full scale applications of one-stage "dry" systems compared to with water diluted "wet" systems. Moreover, slightly higher biogas yields are to be expected in "dry" systems compared to "wet" systems since neither heavy inerts nor scum layer need to be removed before or during digestion. This difference (max. 10% VS difference of destruction for "wet" and "dry" systems) is confirmed by the literature (De Baere, 2000; Weiland, 1993).

Since inhibitors (mainly ammonia for OFMSW) often limit the OLR_{max} of reactors treating OFMSW, the sensitivity of reactor designs towards inhibition is of particular concern. One-stage "wet" reactors generally suffer the disadvantage that the reactor content is fully homogenized. This results on the one hand in the elimination of spatial niches wherein bacteria may be protected from high concentrations of inhibitors. On the other hand, the slurrying of the waste might also lead to an increased solubilisation of nitrogen resulting in higher free ammonia levels in the reactor. However, the slurrying of solid waste also results in a dilution of the ammonia concentration. Kayhanian (1999) showed that by adding fresh water to high-solids waste, the ammonia inhibition effect could be mitigated. In general, for solid wastes with a C/N ratio above 20, the ammonia inhibition effect can be compensated by the dilution effect of water which lowers the concentration of potential inhibitors.

Economical and environmental issues. The economical differences between the "wet" and "dry" systems are small, both in terms of investment and operational costs. The higher costs for the sturdy waste handling devices such as pumps, screws and valves required for "dry" systems are compensated by a cheaper pre-treatment and reactor, the latter being several times smaller than for "wet" systems. The smaller heat requirement of "dry" systems does not usually translate into financial gain since the excess heat from gas motors is rarely sold to the industry (Baeten and Verstraete, 1993).

Differences between the "wet" and "dry" systems are more substantial on environmental issues. While "wet" systems typically consume one m^3 fresh water per ton OFMSW treated, the water consumption of their "dry" counterparts is ca. ten-fold less. Moreover, better hygienization can be achieved with "dry" thermophilic plug flow systems (Baeten and Verstraete, 1993).

Two-stage systems

The rationale of two- and multi-stage systems is that the overall conversion process of OFMSW to biogas is mediated by a sequence of biochemical reactions which do not necessarily share the same optimal environmental conditions. Optimizing these reactions separately in different stages or reactors may lead to a larger overall reaction rate and biogas yield (Ghosh *et al*., 2000). Typically, two stages are used where the first constitutes the liquefaction-acidification compartment, with a rate limited by difficult anaerobically degradable substrates such as the hydrolysis of lignocellulose complexes. The second stage constitutes the acetogenic and methanogenic compartment, with a rate limited by the slow microbial growth rate of the methanogenic bacteria (Liu and Ghosh, 1997; Palmowski and Müller, 2000). With these two steps occurring in distinct reactors, it becomes possible to increase the rate of methanogenesis by designing the second reactor with a biomass retention scheme or other means (Weiland, 1993; Kübler and Wild, 1992). However, the main advantage of a two-stage system is not its higher biogas yield or rate but rather its increased biological stability for wastes which cause unstable performance in one-stage systems (i.e. cellulose-poor wastes with C/N ratios lower than 10).

Without biomass retention

Technical evaluation. The most simple design, used primarily in laboratory investigations, are two complete mix reactors in series (Pavan *et al.*, 2000; Scherer *et al.*, 2000), where wastes are shredded and diluted with process water to ca. 10% TS before entering the first digester.

Another possible design is the combination in series of two plug-flow reactors, either in the "wet-wet" or "dry-dry" mode, as illustrated by the Schwarting-Uhde (Figure 4) and BRV processes, respectively. Both fermenters are upwardly, through-flowing, cylindrical reactors, in which a plug-flow occurs. This is achieved by fitting perforated sheets, which result in a defined residence time. In the first cycle, the tank level in the fermenter is raised within a short time by means of two-way impulse pumps ("in grey", Figure 4). This results in a liquid level drop in the equalizing tank. In this way, local intermixing is forced and gas bubbles which have already been formed are ensured. The more heavy particles sink to the bottom of the reactor and are removed (Trösch and Niemann, 1999). A possible drawback of this technique is the possible occurrence of methanogenesis in the first reactor when hydrolysis becomes rate-limiting.

In the BRV process, the source-separated biowastes, adjusted to 34% TS, pass through an aerobic upstream stage where organics are partially hydrolyzed and ca. 2% organics are lost through respiration. The reason for conducting the hydrolysis stage under microaerophilic conditions is that the loss of COD due to respiration is more than compensated by a higher extent of liquefaction, which, moreover, proceeds faster than under anaerobic conditions (Wellinger *et al.*, 1999; Capela *et al.*, 1999). After a two-day retention time, the pre-digested wastes are pumped through methanogenic reactors in a horizontal plug flow mode. The digestion is set at 25 days at 55°C and 22% TS (after dilution).

Biological performance. As already indicated, the main advantage of the two-stage system is the greater biological stability it affords for very rapidly degradable wastes like fruits and vegetables (Pavan *et al.*, 2000). For instance, short-lived fluctuations of the applied OLR for highly biodegradable kitchen waste will be better buffered with two-stage systems compared to one-stage systems. However, in cases where special care is taken to mix the feed

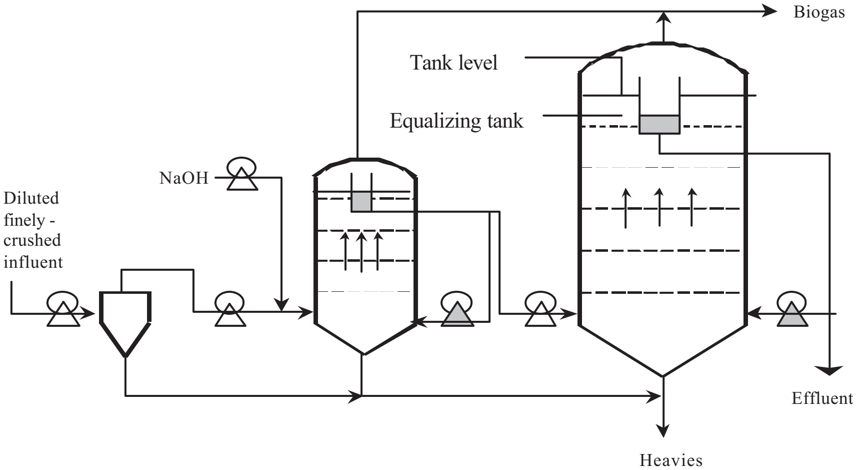

Figure 4 The Schwarting-Uhde process, a two-stage "wet-wet" plug-flow system applicable to source-sorted biowastes, finely-choped (ca. 1 mm) and diluted to 12% TS

thoroughly and dose it at constant OLR, one-stage "wet" systems are as reliable as two-stage systems, even for highly degradable organic wastes.

In terms of biogas yields and OLR_{max}, little difference can be noted between one- and two-stage systems, at least for two-stage systems without a biomass retention system. For example, the BRV plant in Heppenheim is designed with an OLR of 8.0 kg VS/m^3.d while the Schwarting-Uhde process seems to sustain an OLR_{max} up to 6 kg VS/m^3.d (Trösch and Niemann, 1999). The average biogas yields for the BRV-process and the Schwarting-Uhde process are also similar.

With a biomass retention scheme

Technical evaluation. In order to increase rates and resistance to shock loads or inhibiting substances, it is desirable to achieve high cell densities of the slowly-growing methanogenic consortium in the second stage. There are two basic ways to achieve this. The first method to increase the concentration of methanogens in the second stage is to uncouple the hydraulic and solids retention time, thereby raising the solid content in the methanogenic reactor. These accumulated solids represent active biomass only when the wastes do not leave more than 5–15% of their original solid content as residual suspended solids inside the reactor. One way to uncouple the solid and hydraulic retention times is to use a contact reactor with internal clarifier (Weiland, 1993). Another way is to filter the solid waste of the second stage on a membrane and return the concentrate in the reactor in order to retain the bacteria (Madokoro *et al.*, 1999).

Another method to increase the concentration of slowly growing methanogens in the second stage is to design the latter with support material allowing attached growth, high cell densities and high sludge age.

In the BTA "wet-wet" process, methanogenic bacteria are enriched by means of a fixed film loop reactor. The 10% TS pulp leaving the pasteurization step is dewatered and the liquor is directly sent to the methanogenic reactor. The major drawback of this system though is its technical complexity as several reactors are necessary to achieve what other systems achieve in a single reactor.

Biological performance. In two-stage designs with attached growth, greater resistance toward inhibiting chemicals is achieved. While the one-stage system failed at OLR of 4 kg VS/m^3.d for those wastes which yielded ca. 5 g NH_4^+/l due to ammonium inhibition, the same wastes could be processed in the two-stage system at OLR of 8 kg VS/m^3.d without impairment of methanogenesis (Weiland, 1993). It was stated that for residues with a C/N-ratio above 15 the one-step process should be used preferably, whereas protein-rich residues with a C/N-ratio below 10 can be treated only in the two-step process. For the different agro-industrial residues (mainly vegetable matter) it was found that about 50–70% of the organic matter can be degraded within retention times of 10 – 20 days. The biogas production was typically 300–500 m^3 per ton of dry organic matter (Weiland, 1993).

Another consequence of two-stage systems with biomass retention is the possibility of applying higher OLR in the methanogenic reactor, with values up to 10 and 15 kg VS/m^3.d reported for the BTA and Biopercolat processes, respectively (Kübler and Wild, 1992; Wellinger *et al.*, 1999).

Batch systems

In batch systems, digesters are filled once with fresh wastes, with or without addition of seed material, and allowed to go through all degradation steps sequentially either in the "dry" mode, i.e. at 30–40% TS, or in the "wet" mode (15% TS or less). Though batch systems may appear as a landfill-in-a-box, they in fact achieve 50- to 100-fold higher biogas production rates than those observed in landfills because of two basic features. The first is that the leachate is continuously recirculated, which allows the dispersion of innoculant, nutrients, and acids, and in fact is the equivalent of partial mixing. The second is that batch systems are run at higher temperatures than those normally observed in landfills.

Technical evaluation

In the single-stage batch design, the leachate is recirculated to the top of the same reactor where it is produced. This is the principle of the Biocel process, which is implemented in a full-scale plant in Lelystad, The Netherlands, treating 35,000 ton/yr source-sorted biowaste (ten Brummeler, 2000). The waste is loaded with a shovel in fourteen concrete reactors, each of 480 m^3 effective capacity and run in parallel. The leachates, collected in chambers under the reactors, are sprayed on the top surface of the fermenting wastes. One technical shortcoming of this and other batch systems, is the clogging of the perforated floor, resulting in the blockage of the leaching process. This problem can be remediated by limiting the thickness of the fermenting wastes to four metres in order to decrease compaction and by mixing the fresh wastes with bulking material (one ton dewatered digested wastes and 0.1 ton wood chips added per ton fresh wastes) (ten Brummeler, 1992).

In the sequential batch design, the leachate of a freshly filled reactor, containing high levels of organic acids, is recirculated to another more mature reactor where methanogenesis takes place (Figure 5). The leachate of the latter reactor, free of acids and loaded with pH buffering bicarbonates, is pumped back to the new reactor.

Finally, in the hybrid batch-UASB design, the mature reactor where the bulk of the methanogenesis takes place is replaced by an upflow anaerobic sludge blanket (UASB) reactor. The UASB reactor, wherein anaerobic microflora accumulates as granules, is well suited to treat liquid effluents with high levels of organic acids at high loading rates.

Biological performance

The Biocel plant in Lelystad achieves an average yield of 70 kg biogas/ton source-sorted biowaste. This biogas yield is circa 40% smaller than that obtained in continuously fed one-stage systems treating the same type of waste (De Baere, 2000). This low yield is the result of leachate channeling, i.e. the lack of uniform spreading of the leachate which invariably tends to flow along preferential paths. The design OLR of the Lelystad plant is 3.6 kg VS/m^3.d at 37°C. Waste peak values of 5.1 kg VS/m^3.d during summer months can be handled (ten Brummeler, 2000).

Economical and environmental issues

Because batch systems are technically simple, the investment costs are significantly (ca. 40%) lower than those of continuously fed systems (ten Brummeler, 1992). The land area required by batch processes is however considerably larger than that for continuously fed “dry” systems, since the height of batch reactors is about five-fold less and their OLR

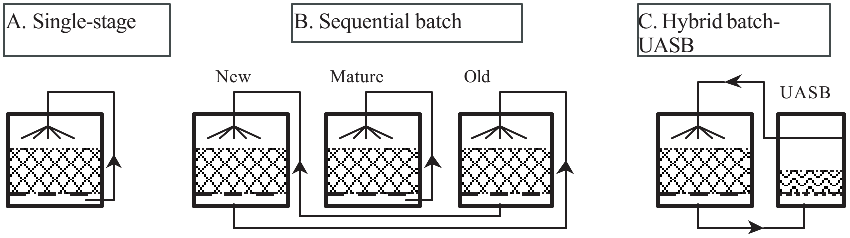

Figure 5 Configuration of leachate recycle patterns in different batch systems

two-fold less, resulting in a ten-fold larger required footprint per ton treated wastes. Operational costs, on the other hand, are comparable to those of other systems (ten Brummeler, 1992).

Future perspectives and conclusions

A remarkable evolution has occurred in the attitude towards in-reactor digestion of solid wastes. The scepticism with respect to the feasibility has changed towards a general acceptance that various digester types are functioning at full scale in a reliable way.

Considering the anaerobic digestion of both grey wastes (residual refuse which remains after source separation) and OFMSW, a very high growth potential is to be expected. For the digestion of grey wastes which can contain up to 60% of biodegradable waste, a general tendency can be noticed towards maximum energy recovery and recycling: the low-calorific organic fraction is converted into biogas and the high calorific fraction is thermally treated (i.e. incineration or gasification). A remaining fraction (non-energy fraction) can be recycled. An example of such a multiple reuse scheme is given in Figure 6. In order to separate the low calorific fraction (up to 60%, mainly organic matter) from the high calorific fraction (up to 40% such as plastics) and the ferro/non-ferro stream, a dry mechanical separation is applied by means of different kinds of sieves with apertures of different width (i.e. fraction > 150 mm is classified as RDF and is sent to the plasma treatment). Next, the low calorific waste stream is sent to a solid-waste digester. A “dry” one-stage digester is particularly suited in the treatment of grey waste because of its high flexibility (wastes with TS content between 20 and 50% can be handled and impurities do not cause any hindrance) and the high OLR that can be achieved. By means of wet mechanical separation, different material fractions can be recovered and reused with high efficiency. Both the digester residue and the high calorific waste stream can be treated in a plasma system after conditioning (i.e. drying, compaction, size reduction). The syngas and biogas can both be used for electricity production while the lava has excellent properties for application in road infrastructure (Calaminus and Stahlberg, 1998).

As a whole, it must be recognized that anaerobic digestion of solid wastes (particularly OFMSW) still has to compete vigorously with aerobic composting. This is in part related to the fact that composting is a long-established technology which generally requires less

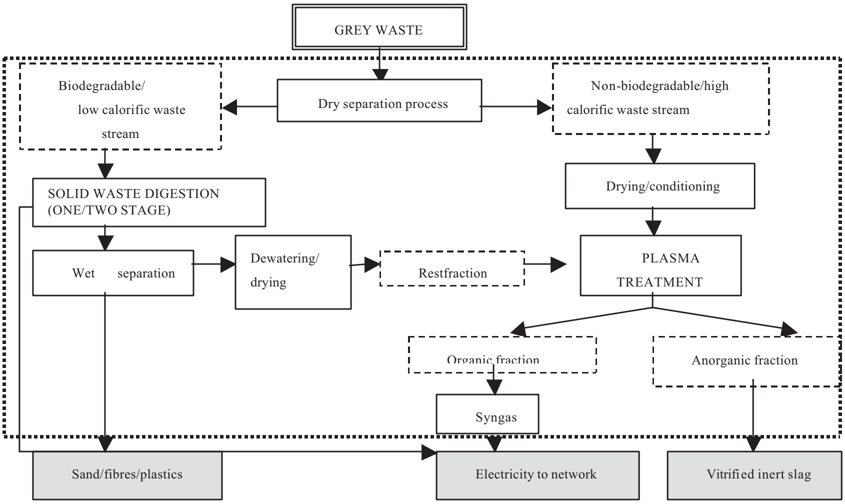

Figure 6 Overview of an integrated grey waste treatment method for maximum material and energy recovery

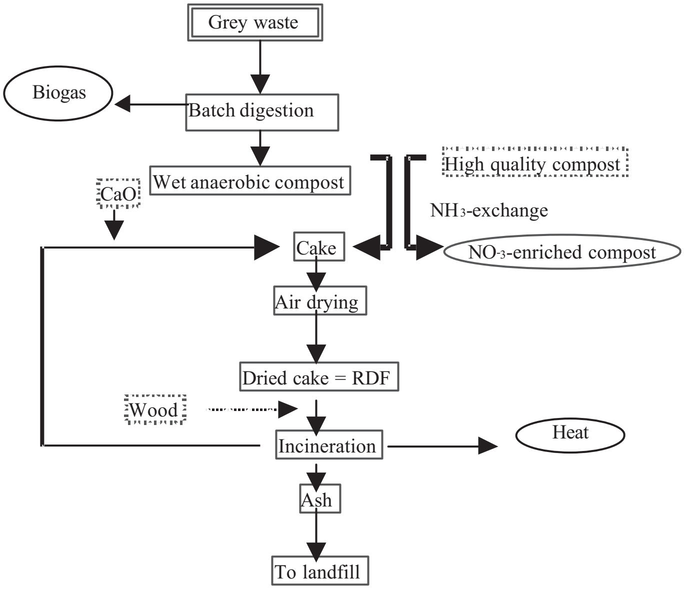

Figure 7 The total recycle process for grey MSW referred to as Multiple Integrated Reuse of Refuse (MIROR). The recovery products are encircled, the processes are squared and the optional supplementation products are dotted

initial investment. However, current energy prices and targetted reduction of fossil fuel combustion in the coming decades will draw increasingly more attention towards anaerobic digestion.

A future concept of a totally different type for the treatment of grey household waste is schematized in Figure 7 (Biey *et al.*, 2000). This concept makes use of a batch digestion system and offers application in developing countries. The remaining RDF-fraction can be thermally valorized by means of a stove.

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