This is a revised personal version of the text of the final journal article, which is made available for scholarly purposes only, in accordance with the journal's author permissions. The full citation is:

Dogan Karadag, Oguz Emre Koroglu, Bestami Ozkaya, Mehmet Cakmakci, Sonia Heaven, Charles Banks and Alba Serna-Maza. (2015). Anaerobic granular reactors for the treatment of dairy wastewater: A review. International Journal of Dairy Technology. Vol 68, 1-12 DOI: 10.1111/1471-0307.12252

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**A review of granular reactors for the anaerobic treatment of dairy wastewater**

Dogan Karadag1,2,\*, Oguz Emre Koroglu1, Bestami Ozkaya1, Mehmet Cakmakci1, Sonia Heaven2, Charles Banks2 and Alba Serna-Maza2.

1Yildiz Technical University, Department of Environmental Engineering, Davutpasa, Istanbul, Turkey

2Faculty of Engineering and the Environment, University of Southampton, SO17 1BJ, UK

**Abstract**

Considerable research has been conducted on the treatment of dairy wastewater by anaerobic granular reactors: the present paper provides a comprehensive evaluation of recent articles on this theme. Upflow anaerobic sludge blanket (UASB) reactors, anaerobic sequencing batch reactors (ASBR) and static granular bed reactors (SGBR) are the conventional granular reactor types most commonly applied in dairy wastewater treatment. Hybrid systems have also been developed to increase treatment efficiency and overcome the operational problems associated with treatment of this substrate in individual reactors. Effects of parameters including temperature, organic loading and operating protocols on the performance of granular reactors are summarized. Individual and hybrid granular reactors are evaluated based on organic matter removal and methane production capacity.

**Keywords:** Dairy wastewater; granular reactor; methane; organic loading.

\*Corresponding author: email dogankaradag@gmail.com

**1 Introduction**

A billion tonnes of dairy products are consumed worldwide each year, and global demand has been increasing significantly with rising population and living standards (Faye and Konuspayeva, 2012). Dairy production facilities are one of the most important industrial wastewater sources, since a large volume of water is used in all production steps and in equipment cleansing. Effluents from dairy production systems are rich in carbohydrates, proteins and fats which are major sources of wastewater pollution (Prazeres et al., 2012; Traversi et al., 2013). Dairy process wastewaters are typically high-strength effluents with high concentrations of organic matter, suspended solids and oil-grease along with varying amounts of other pollutants (Table 1).

Anaerobic treatment has the dual benefits of reducing pollution and producing renewable energy, and dairy process wastewater with its high organic content is thus a valuable potential resource for energy production. In anaerobic conditions, organic matter can be directed towards the production of hydrogen (H2) or methane (CH4). A previous review (Karadag et al., 2014) showed how conventional anaerobic reactors and hybrid systems have been successfully employed to convert dairy industry wastewaters to H2. In comparison to H2 generation, CH4 producing systems convert all organics to final products, and are less sensitive to changes in operational conditions (Shuizhou et al., 2005).

Anaerobic reactors can be operated using suspended, granular or biofilm microorganisms. The superior settling characteristics of granules allow higher biomass concentrations to be maintained in the reactor and prevent the easy washout of microorganisms: compared to other reactor types, granular reactors may also have the advantages of withstanding shock loads, and of stable operation under high organic loadings (Leitão et at, 2006, Couras et al, 2014, Lim and Kim, 2014). Upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB) and anaerobic sequencing batch reactors (ASBR) are well known high-rate granular reactors and have been successfully employed for the treatment of high-strength wastewaters from different sources (McHugh et al., 2003; Turkdogan et al., 2013).

Although many anaerobic systems have been documented for the treatment of dairy industry wastewaters (Demirel et al., 2005; Arbeli et., 2006; Lim and Kim, 2014), there is no report focusing specifically on the treatment of dairy wastewater by anaerobic granular reactors. In the present work, publications on anaerobic granular reactors treating dairy wastewater have been reviewed from the viewpoint of operational strategies and performance has been compared on the basis of organic matter removal and methane production.

Table 1 here

**2 Anaerobic granular reactors**

Anaerobic granular reactors have proven successful for treatment of high strength food-processing wastewaters (Ibrahim et al., 2013; Kushwaha et al., 2013; Rajagopal et al., 2013). Reactor studies on dairy wastewaters have mostly been conducted in a pH range of 6.6-7.2 (Hawkes et al., 1995; Buntner et al., 2013), while some researchers have operated at higher pH (7.1-7.6) (Banu et al., 2008). In some cases the desired pH in the reactor has been maintained by adding acid or basic chemicals (Gavala et al., 1999; Banu et al., 2008), while in other studies wastewater was fed directly to the reactor without pH adjustment (Passeggi et al., 2012). A decrease in pH is usually associated with accumulation of volatile fatty acids (VFA) within anaerobic reactors and this is especially common in the start-up period when the reactor performance in terms of removal of organics and production of CH4 is lower. In order to prevent the rapid increase of VFAs, the reactor needs to have a sufficient quantity of alkalinity. The required alkalinity can be supplied by addition of buffer chemicals such as NaHCO3 (Gutierrez et al., 1991; McHugh et al., 2006), NaCO3 or NaOH (Bandara et al., 2011; Kalyuzhnyi et al., 1997) into the wastewater feed or directly to the reactor. On the other hand, anaerobic degradation of proteinaceous compounds in the dairy wastewater releases amino groups and ammonia which contribute to the generation of alkalinity (Rajeshwari et al., 2000). Banu et al. (2008) reported an improvement in the alkalinity of an anaerobic reactor treating dairy wastewater due to the increase in protein content when the wastewater concentration was increased.

Studies on dairy wastewater treatment in anaerobic granular reactors have mainly been performed at mesophilic temperatures such as 30 °C (Mockaitis et al., 2006; Ganesh et al., 2007) or 35-37 °C (Kim et al., 2004; Leal et al., 2006; Najafpour et al., 2008). Only a few studies have been conducted at psychrophilic (10 oC, Bialek et al., 2013; 20 °C, McHugh et al., 2006., Tawfik et al., 2008) and thermophilic temperatures (55 °C) (Zielinska et al., 2013). The main drawbacks of anaerobic treatment at psychrophilic temperatures are the decrease in CH4 in the gas phase due to increased solubility at lower temperatures; and the low growth rate of the methanogenic community. Researchers were able to recover dissolved methane and increase COD removal efficiency by installing a degassing membrane unit at the outlet of an UASB reactor (Bandara et al., 2011).

Heating of granular reactors has been accomplished by water jacket (Gutierrez et al., 1991; Najafpour et al., 2008), electrically (Hawkes et al., 1995), microwave (Zielinska et al., 2013) or maintaining the reactor in a temperature-controlled room (Kundu et al., 2013; Ramasamy et al., 2004). Zielinska et al. (2013) compared the effect of microwave and water jacket heating on the performance of anaerobic hybrid reactors. It was reported that microwave heating significantly improved biogas production by enhancing methanogenic diversity. Similarly, other researchers reported that improvement in CH4 production with microwave-heated anaerobic reactors is associated with improvements in of microbial diversity and growth (Banik et al., 2003; Kwiatkowsk et al., 2012).

Granular reactors have been fed on real dairy wastewater from whey production (Gavala et al., 1999; Erguder et al., 2001), ice-cream production (Goodwin et al., 1990; Hawkes et al., 1995; Borja and Banks 1994), cheese production (Gutierrez et al., 1991) or simulated wastewater was prepared by mixing whole milk or milk powder with water (Haridas et al., 2005; Belancon et al., 2010). In their study, Ganesh et al. (2007) used washing wastewater from a dairy plant as substrate in a UASB. Some researchers initially fed reactors with simulated substrate or diluted dairy wastewater to adapt the microbial consortium to operational conditions (Belancon et al., 2010). The other strategy applied for easily adaptation was operation in batch mode before continuous feeding (Kalyuzhnyi et al., 1997; Ganesh et al., 2007). In continuous reactor systems, the amount of substrate is commonly optimized based on organic loading rate, which can be adjusted by changing influent COD concentration or HRT. It was reported that mass transfer and anaerobic degradation rates are more favourable at high OLR, while slow-growing methanogens are easily washed out at lower HRTs (Kundu et al., 2013).

**3 Upflow anaerobic sludge blanket reactors**

Compared to other anaerobic reactors, UASB have some advantages, such as simple construction, low operational cost and high organic removal efficiencies (Latif et al., 2011). At relatively short HRTs, UASB can develop a high concentration of granular sludge with good settling properties and a rich methanogenic population (Ozgun et al., 2013). UASB operation on dairy wastewater has been initiated by transferring granules from other UASB reactors (Borja R, Banks, 1994) or by self-granulation from various inoculum sources (Goodwin et al., 1990; Hawkes et al., 1995). Ramasamy et al. (2004) investigated the treatment of dairy wastewater by two UASBs with self-granulated and transferred granules. It was reported that the self-granulated UASB gave lower organics removal at the initial operational stage but there was no difference in the performance of both reactors in long-term operation.

In self-granulation, the start-up procedure is crucial for the development of granules with high methanogenic activity and good settling properties. The long start-up time of up to several months is a bottleneck in UASB operation, however Najafpur et al. (2008) were able to shorten the start-up duration by developing tubular flow in a UASB reactor. McHugh et al. (2006) reported that inoculation with a high concentration of well-settling granular sludge contributes to successful and rapid start-up of reactors. Granules developed from sludge with low volatile solids and poor settling characteristics lead to easy washout of micro-organisms, low organics removal and poor biogas production. The carbon content of the wastewater also significantly affects the physical structure and microbial diversity in granules, while the presence of carbohydrates and additives such as natural and cationic polymers can improve granulation (Yang and Anderson 1993; Ramasamy et al., 2004). Vlyssides et al. (2008) reported that Fe2+ supplementation provided a 56% increase in granule diameter in a UASB. The positive effect of iron was associated with the generation of inert nuclei from ferrous sulphide precipitates with attachment of biomass around the nuclei. Iron accumulation within granules also interacts with exopolysaccharide polymers along with sulphide ions, and the granule colour can become darker (McHugh et al., 2006). The structure and functions of granular layers have also been well documented by researchers. Satoh et al. (2007a and b) performed microsensor measurements in granule layers from a UASB treating dairy wastewater and revealed that granules have considerable microbial diversity and different anaerobic processes are carried out in different distinct layers of a granule. Complex organics are hydrolysed at the surface of the granule while simple organics are fermented to fatty acids, alcohols and H2 in the middle layers, then CH4 is produced in the inner layers.

Organic loading rate has a considerable effect on granulation; however, conflicting results have been reported on the relationship between these parameters. Although rapidly increasing OLR was reported as helping to enhance granule formation (Hawkes et al., 1995; Gutierrez et al., 1991), some researchers have indicated that a sudden increase in OLR can cause loss of specific sludge activity, washout of granules and reduction in COD removal efficiency (Yan et al., 1988; Ramasamy et al., 2004). Ramasamy et al. (2004) recommended start-up of UASB with a low organic loading of 2.4 kg COD m-3 d-1 to allow easy acclimation to dairy wastewater. It has been reported that the addition of more readily biodegradable carbon sources, such as methanol, in the start-up period can improve granule formation, settling velocity and reactor stability (Cayless et al., 1990). On the other hand, high nitrogenous content in the wastewater may increase sludge loss by up to 60% due to the agitation of the granular bed by nitrogen bubbling (Yan et al., 1989; Goodwin et al., 1990). Design faults in the phase separator and high lipid content of wastewater may negatively affect granulation, while a low acetate concentration inside the UASB reactor enhances granulation (Hawkes et al., 1995). Additionally, anaerobic bacteria treating whey tend to produce large amounts of sticky exopolymers which adversely affect granulation (Janczukowicz et al., 2008).

*Effect of organic loading on UASB*

Comprehensive studies have been performed to optimize OLR values and incrementing strategies for efficient UASB operation, but contradictory results have been reported for dairy wastewater treatment. Variations in optimum OLR values have been related to differences in wastewater characteristics, operational conditions and design parameters for UASB. Applied OLR values in UASB studies and performance comparisons with other reactors are given in Table 2. For successful operation of UASB on whey, step-wise increment of influent COD is recommended (Yan et al., 1989) and VFA concentrations should be closely monitored before changing OLR since the highest CH4 production could be obtained at the lowest acetic and propionic acid levels (Yan et al., 1988). Yan et al. (1989) obtained 97% COD removal with 57% CH4 content at OLR of 2 kg COD m-3 d-1 for whey treatment, while Gavala et al. (1999) reported that OLR up to 7.5 kg COD m-3 d-1 has no negative effect on UASB stability. Yan et al. (1993) suggested the optimal influent concentration for system stability at an HRT of 5 days was 25-30 g COD L-1, corresponding to an OLR of 5 kg COD m-3 day-1. Yu et al. (2002) reported that biogas production from simulated dairy wastewater increased with increasing OLR up to 12 kg COD m-3 d-1, whereas further increases in OLR negatively affected the performance of UASB at both mesophilic and thermophilic temperatures. Kalyuzhnyi et al. (1997) obtained stable COD removal of over 90% for the treatment of whey without sludge washout at 35 °C when a UASB was operated at OLR of 28.5 kg COD m-3 d-1, but further increases in OLR caused washout and deterioration in the reactor performance. When the temperature was reduced to 25 °C, the microbial community rapidly adapted to the new conditions and gave a COD removal efficiency of greater than 90% at OLR of 7.0-9.5 kg COD m-3 d-1. The authors concluded that the OLR limit to avoid washout in UASB at sub-mesophilic temperatures is 9.5 kg COD m-3 d-1 and the optimal OLR for whey treatment at 35 °C is 28.5 kg COD m-3 d-1.

Yan et al. (1988) indicated that increasing the OLR by decreasing HRT is more effective than increasing COD concentration in terms of maintaining the microbial community structure and methane production in UASB treating dairy wastewater. However, different optimum HRT values have been reported for stable UASB operation on dairy wastewater. Hwang et al. (1992) recommended keeping the HRT above 0.8 d for successful operation of UASB, while Gutirrez et al. (1991) obtained stable COD removal of around 97% at HRT of 0.17 d. Erguder et al. (2001) stated that 95-97% COD removal from whey is possible at HRT values of 2–5 d. On the other hand, UASB operation at very short HRT promotes VFA generation, while accumulation of propionate deteriorates reactor performance by inhibiting methanogenic archaea. Similarly, Borja and Banks (1994) instability in UASB performance when HRT was reduced from 5 d to 0.4 d during the treatment of ice-cream processing wastewater.

*Effect of temperature on UASB performance*

Treatment studies of dairy wastewater in UASB have mainly been conducted in mesophilic temperatures (Vlyssides et al., 2009; Goodwin et al., 1990; Borja R, Banks, 1994) while a few UASB reactors have been operated in the thermophilic range. Thermophilic UASB treatment of dairy wastewater has mainly been conducted as a preliminary acidification step (Yu and Fang, 2000). Operation of UASB fed on simulated milk wastewater at 37 and 55 °C indicated that temperature has no effect on COD reduction and acidification level; however, biogas production was higher at thermophilic temperature (Yu et al., 2002). In recent years, operation of anaerobic reactors at psychrophilic temperatures has gained great attention since there is no need for an energy input to maintain higher temperatures (Colins et al., 2013). During the operation of anaerobic reactor at lower temperatures, microbial growth rate and methanogenic activity decreases and biomass washout occurs (Janczukowicz et al., 2008; Akila and Chandra 2007). In order to overcome these disadvantages, psychrophilic reactors are recommended to operate at higher HRT (Chu et al., 2005) and to start up with a large amount of biomass (Rebac et al., 1999).

Operation of two-phase UASB reactors has been recommended for efficient treatment of dairy parlour wastewater at ambitious temperatures (Luostarinen and Rintala, 2005). Start-up of a UASB reactor with mesophilic digester sludge and stepwise decreasing of the reactor temperature prevented the washout of biomass and provided over 80% COD removal at 10, 15 and 20 °C. At 30 ºC, Ramasamy et al. (2004) obtained over 96% COD removal by UASB at HRT of 3 h but this decreased slightly when the HRT was increased to 12 h. The highest COD reduction was at OLR of 10.5 kg COD m-3 d-1 and reactor performance dropped when OLR was further increased. The researchers indicated that optimal reactor performance for the treatment of dairy wastewater could be obtained with HRT of 3 h and OLR of 13.5 kg COD m-3 d-1. Buntner et al. (2011) operated a UASB reactor for the treatment of low-strength dairy wastewater (600 mg COD L-1) at an ambient temperature range of 23-17.5 °C. They reported that the UASB had high tolerance to changes in temperature and organic loading, while COD removal efficiency and methane content were around 80%.

Tawfik et al. (2008) employed different operational schemes to overcome the difficulties in psychrophilic operation of UASB. Domestic wastewater was mixed with dairy influent at 30% since it has easily biodegradable organics, and a high solid retention time (76 days) was applied. Achievement of constant organic removal efficiencies with the average values of 69 % COD along with 72% total suspended solids (TSS) removal were associated with effective hydrolysis and degradation at long sludge retention times. The highest reactor performance was obtained at OLR of 3.4 kg COD m-3 d-1 and regular intentional sludge discharge from the UASB prevented wash-out of granules. Application of activated sludge treatment after the psychrophilic UASB provided an excellent overall COD removal of 98.9%.

*Effect of supplementation with trace elements*

It has been reported that supplementation of nutrients and trace metals significantly improves COD removal and biogas production in UASB (Hawkes et al., 1992). Murray and van den Berg (1981) reported that supplementation of Ni2+, Co2+ and Mo2+ enhanced the treatment performance of food industry wastewater in UASB by increasing the amount of methane-producing archaea. During the treatment of undiluted whey, Erguder et al. (2001) achieved the operation of UASB at lower HRT (2-5 d) by supplementation with nutrients and trace elements. It has been reported that Zn2+ up to 10 mg L-1 slightly enhances acidogenesis while Cu+2 is toxic even in trace amounts during the treatment of dairy wastewater. The inhibitory effects of Zn+2 and Cu+2 increase at higher concentrations while Cu+2 is 1.4-4.3 times more toxic than Zn+2 in degradation of carbohydrates and protein (Yu et al., 2001). Vlyssides et al. (2012) obtained over 98% COD removal during the treatment of simulated milk wastewater with ferrous iron addition, which was 24% higher than for a control reactor not receiving ferrous iron. The researchers indicated that iron addition increases anaerobic treatment performance by promoting microbial growth, granule diameter, absorption of carbon materials and precipitation of sulphate (Vlyssides et al., 2007).

Table 2 here

*Operational problems in UASB*

Dairy wastewater contains a significant quantity of lipids, and accumulation of these in a UASB causes several operational problems including sludge flotation, biomass washout, mass transfer reduction, impairment of sludge settling capacity and lower sludge activity (Passeggi et al., 2012). The research indicated that the lipid concentration should be less than 100 mg L-1 for successful treatment of dairy wastewater in mesophilic conditions. On the other hand, Leal et al. (2006) reported that dairy wastewater with a high lipid content of up to 1000 mg L-1 could be successfully treated in UASB. Degradation of lipids could be improved by addition of extracellular enzyme or application of pre-treatment. The researchers applied various pre-treatment methods to prevent lipid-related problems. It has been reported that Fenton oxidation before a UASB reactor could be a solution for this problem (Yu et al., 2001). Fenton oxidation removed 80% of lipids by converting them into soluble organics or fully mineralizing them. Fenton treatment plus UASB provided satisfactory COD removal of over 90%, along with 85% methane content at 27 °C. Ferrous iron addition through Fenton oxidation also enhanced the sludge activity and granule formation, with excellent carbon removal and also sulphide precipitation. Cammarota et al. (2001) obtained COD removals below 50% during the operation of UASB fed on dairy wastewater with a high lipid content. Leal et al. (2006) hydrolysed dairy wastewater with the enzyme of *Penicillium restrictum* and obtained COD removal efficiencies of 90% at low FOG concentrations. However, COD removal efficiency decreased from 91% to 82% when the FOG concentration in the raw wastewater increased from 200 to 1000 mg L-1. Accumulation of lipids under the biogas hood in UASB also prevents effective escape of biogas and causes break-up of the UASB bed, which results in poorer contact between microorganisms and substrate with limited biofilm formation and lower methane yields (Gutierrez et al., 1991; Hawkes et al., 1995). Blonskaja and Vaalu (2006) recommended sludge recirculation from a sedimentation tank to the UASB to prevent biomass washout.Passeggi et al. (2012) recirculated biogas bubbles into a UASB to enhance the gas escape and obtained enhanced treatment efficiency.

LCFA is a hydrolyzed product of lipids, and LCFA accumulation causes operational problems, including limited substrate removal and decrease in reactor performance (Pereira et al., 2003; Alves et al., 2001). Proper design of the UASB is important, otherwise the small reactor diameter may cause a piston effect resulting in biomass flotation even at very low LCFA concentrations. Inhibition by high concentrations of LCFA could be eliminated by dilution, addition of adsorbents and changing feeding patterns. Palatsi et al. (2009) indicated that adsorbent addition is a more reliable strategy for industrial treatment plants while bentonite binds LCFA and improves the recovery time of the anaerobic reactor.

Intermittent feeding has been proven effective as a method to improve the performance of various anaerobic reactors during the treatment of complex wastewaters with a high lipid content (Nadais et al., 2006; Del-Pozo et al., 2000; Neves et al., 2009). In intermittent operation, feeding of the reactor is stopped for a certain time to allow complete degradation of substrates accumulated within the reactor. Nadais et al. (2011) compared the performance of continuous-fed and intermittent-fed UASB for dairy wastewater treatment and obtained enhanced COD removal and 25% higher methane production with intermittent feeding. The improvement in reactor performance was related to higher organic matter degradation and better adaptation of the biomass to the complex substrates. Furthermore, Nadais et al. (2005) achieved an increase in OLR of up to four times with intermittent operation when treating dairy wastewater in UASB.

Methanogenic archaea in UASB are sensitive to inhibition by dissolved oxygen, toxic chemicals, ammonia, accumulated VFA and heavy metals (Yenigun and Demirel, 2013). Buntner et al. (2011) reported that inhibition of methanogens due to a high concentration of methanol reduced COD removal below 20% with CH4 content less than 50%. Accumulation of VFA is a common problem with UASB operation, where it causes a decrease in pH and inhibits methanogenic activity (s et al., 2003). Among the VFAs, the amount of propionate should be monitored closely since it is toxic to methanogens at concentrations higher than 2000 mg L-1 (Yan et al., 1988; Kundu et al., 2013). Problems related to VFA accumulation could be eliminated by addition of alkalinity or by decreasing the OLR. Ghally et al. (2000) recommended reseeding the UASB only if alkaline addition did not recover the reactor. Mixing of dairy wastewater with other waste streams may also prevent inhibition of the methanogenic community. Demirel et al. (2013) reported that ice-cream production residues contain a large amount of sulphate and mixing them with wastewater from an ice-cream producing plant at appropriate ratios eliminated sulphur inhibition. Chemicals in wastewater from the control laboratory in a dairy industry plant could be highly toxic for methanogens, and mixing with other effluents is beneficial for efficient anaerobic degradation (Lopez-Fiuza et al., 2002).

*Different operational schemes for UASB*

When an anaerobic reactor fails due to low pH , a two-stage process becomes essential for improving the biogas production rate and methane yield (Rajeshwari et al., 2000). Higher performance and stability were reported when dairy wastewater was treated in a two-stage UASB system. In two-stage operation, wastewater is acidified in the first reactor and CH4 is produced in the second reactor. Generally, a CSTR is installed prior to the UASB to acidify the dairy wastewater. Diamantis et al. (2014) compared the performances of varying configurations of CSTR and UASB. The experimental results indicated that the use of a CSTR followed by biomass separation and recirculation prior to the UASB provided complete acidification of carbohydrate and higher COD removal of up to 90%, along with superior methane yield. Recirculation of separated biomass to the CSTR also eliminated alkali addition and the UASB achieved a stable treatment performance at OLR values of up to 20 kg COD m-3 d-1.

Kim et al. (2004) compared the effect of LCFA on the performance of single-stage UASB and a two-stage system of CSTR plus UASB. They reported that LCFA did not cause significant problems in two-stage systems up to 3.5-4.0 g LCFA-COD L-1, and COD removal was over 95%. Two-stage treatment gave stable organic removals in all conditions; whereas the performance of a single-phase system deteriorated when the influent wastewater had 4.0 g LCFA-COD L-1. Degradation of lipids in a CSTR enhanced UASB stability and treatment efficiency. The two-stage treatment provided 1.19 and 1.42-fold higher COD removal and CH4 production, respectively (Kim et al., 2006).

In some cases, a UASB is inadequate to meet discharge limits and requires a post-treatment step for dairy wastewater. The application of a membrane bioreactor (MBR) after UASB was reported with excellent COD and suspended solids removal in stable operational conditions, while no or very little nitrogen and phosphorus reduction was achieved (Buntner et al., 2011). Buntner et al. (2013) combined a UASB with a two-compartment aerobic MBR for the treatment of dairy wastewater at ambient temperatures (17-25 °C). The UASB and the combined system were operated at HRTs of 10, 15 and 11 h for the UASB and 14, 20 and 15 h for the combined system. COD removal was 66-85% after the UASB while it increased to 99% in the combined system along with 73% methane content. Erguder et al. (2001) operated two UASB reactors in series for the treatment of whey and stated that the second UASB gave a slight improvement in COD removal; however, this enhancement could be achieved by increasing the HRT of a single-stage UASB.

**4 Other granular reactors**

*Anaerobic sequencing batch reactor*

Anaerobic sequencing batch reactor (ASBR) can be operated with granular or immobilized biomass (Fuzzato et al., 2009) and have been successfully employed for the treatment of dairy and other wastewaters (Dugba et al., 1999; Mockaitis et al., 2006; Bodik et al., 2002). Ndon and Dague (1997a, 1997b) studied the treatment of low-strength non-fat dry milk wastewater in an ASBR at various temperatures, substrate concentrations and HRTs. Granule development was observed at a HRT of 12 h while no granulation was present when the HRT was increased. Granule formation at this short HRT was due to the selection of good settling particles at higher hydraulic loadings while lighter particles were washed out of the reactor. Operation of the ASBR at higher organic loadings is recommended for the treatment of low-strength wastewater since the OLR provides the necessary nutrients for granules. The granular ASBR achieved over 85% COD removal at all substrate concentrations when operated at temperatures over 15 °C; however, treatment performance at 15 °C declined at elevated substrate concentrations. The deterioration in CH4 production at lower temperature was associated with biomass washout due to the low biomass settling velocity. Similarly, Banik et al. (1997) investigated the effect of lower temperatures (5, 15 and 25 °C) on granule activities in an ASBR treating non-fat dry milk. The ASBR was inoculated with mesophilic biomass and no significant variation was observed in the microbial community when the temperature was decreased stepwise. At lower temperatures, mesophilic bacteria were active and had the capability for rapid degradation of organics to acetate and propionate even after prolonged operation. Mockaitis et al. (2006) employed an ASBR containing granular biomass for the treatment of whey at 30 °C. The mechanically-stirred reactor gave stable treatment performance at all organic loadings studied, and achieved organic matter removal efficiencies close to 90%. Addition of sodium bicarbonate as a buffering chemical increased the organic loading capacity of reactor. Biomass flotation occurred due to release of carbonic gas, however, and the amount of floating biomass increased with increasing alkalinity supplementation. Pretti et al. (2011) compared the performance of an ASBR and an anaerobic sequencing biofilm batch reactor (ASBBR) for treatment of wastewater from a dairy plant after fat separation, and found the ASBR gave superior performance especially at a 24 h cycle time. Matsumoto et al. (2012) used an ASBR followed by an aerobic sequencing batch reactor to maximise removal of organics and nitrogen: the ASBR was able to achieve 91% COD removal over a 24-h cycle at an OLR of 4.5 kg COD m-3 day-1.

*The static granular bed reactor*

The static granular bed reactor (SGBR) is a novel anaerobic reactor which has no mixing process and can offer significant energy savings. The reactor operates in downflow mode while the upper part contains a headspace for gas collection (Debik et al., 2009). During the treatment of simulated wastewater composed of non-fat dry milk and sucrose, the SGBR demonstrated significantly higher performance at a HRT of 8 h with an average COD removal of 90.7% compared to 77.5% in a UASB (Evans and Ellis, 2005 and 2010). A pilot-scale (42.5 m3 working volume) SGBR treating dairy processing wastewater at ambient temperature (10-29 oC) in Tulare, California was operated for 7 months at HRT from 9-48 hours and OLR from 0.63-9.72 kg COD m-3 d-1. The system consistently achieved over 90% COD removal and average TSS removal was over 80% (Park et al., 2012). Trials at the same site using a 5.7 m3 pilot-scale SGBR showed significant accumulation of undegraded particulate organics at HRT of less than 18 h and OLR greater than 3.5 kg COD m-3 d-1, especially at lower temperatures; these were removed by backwashing through valves in the side of the reactor (Oh et al., 2014).

*Hybrid reactors*

Hybrid reactors have been developed by combining the properties of granular and biofilm systems to increase the treatment efficiency of conventional granular reactors (Najafpaur et al., 2008; Passeggi et al., 2012). Hybrid systems are constructed by modifying conventional anaerobic reactors. In two-compartment reactors, granule and biofilm communities are grown in different compartments and work simultaneously. Wastewater is firstly fed to the granule-containing compartment at the bottom of the reactor and a biofilm is developed on various support media in the upper part of the reactor. These reactors have been reported to provide a buffering effect against shock loading (McHugh et al., 2006; Strydom et al., 1997).

Cordoba et al. (1995) converted the flow mixing chamber of an anaerobic filter, comprising 30% of the total reactor volume, into a UASB. Formation of granules was observed after 4 weeks of operation on a dairy industry wastewater at 30 oC. Performance was compared to that of an unmodified anaerobic filter. It was found that the hybrid filter achieved 40% higher COD removal efficiencies and 65% higher volumetric gas production. OLR could also be increased more rapidly on the hybrid system. Strydom et al. (1995) examined the performance of a hybrid UASB – fixed bed reactor fed on synthetic dairy wastewater in response to stepwise changes in influent concentration (3.7-10.3 g COD l-1) and in HRT (1-7-4.1 days). The optimum methane yield was achieved at 1.9 day HRT. It was concluded, however, that a two-phase system would be necessary for full-scale treatment.

Belancon et al. (2010) established a hybrid UASB with polyurethane support material above the gas-liquid separation zone to improve solids retention. The reactor was fed with dairy wastewater and operated at 30 °C at a HRT of 1 d. Inserting the supporting media increased the biomass amount and the reactor remained in stable condition despite the loss of 18% of biomass due to flotation of granules. Organic matter removal was 86% in the sludge bed while biofilm bed improved COD removal up to 93% with a methane production rate of 1.8 L L-1 d-1.

Haridas et al. (2005) operated a Buoyant Filter Reactor (BFBR) for the treatment of simulated dairy wastewater. Reactor liquor content was mixed by biogas recirculation and a scum recirculation facility was installed into the reactor to improve mixing. The BFBR was operated at a HRT range of 7.5-11.3 h and the start-up period lasted several months. In the reactor, granulation occurred by an unknown mechanism and the sludge was in irregular granule shape with a size of 2 mm. Organic matter removal gradually improved with ageing of the sludge and COD removal efficiency was above 85% at all organic loadings. The highest COD removal was 90% at maximum OLR of 10 kg COD m-3 d-1 with the methane yield of 0.37 m3 kg-1 COD. Scum formation inside the BFBR was observed during the increment of OLR; however, the accumulated scum was degraded when wastewater feeding stopped.

Ozturk et al. (1993) operated a lab-scale hybrid UASB (HUASBR) for the treatment of dairy wastewater at mesophilic conditions. The bottom 40% of the HUASBR was designed as a UASB and the upper 60% was filled with cylindrical plastic rings. The HUASBR was operated at a HRT of 0.21-0.96 d and the OLR was gradually increased from 2.54 to 17 kg COD m-3 d-1. The highest COD removal was 87% at 10 kg COD m-3 d-1 and a HRT of 18 h. The researchers also reported that rapid OLR increment caused some problems in the gas-liquid separator. However, the stability of the reactor was not negatively affected by increasing OLR up to 17 kg COD m-3 d-1 with an average COD removal efficiency of 75%.

McHugh et al. (2006) constructed a hybrid EGSB by separating it into three chambers through installing a circular baffle with a ball to retain more biomass within the system. The researchers investigated the effect of OLR and temperature on the treatment of high strength whey (10 g COD L-1). The temperature was changed from 20-12 °C by decreasing 2 °C at every step. COD removal was between 90-95% and the reactor gave a stable performance with low VFA concentrations when temperature was stepped down. The highest COD removal was at 14 °C and an OLR of 13.3 kg COD m-3 d-1. When the temperature was reduced to 12 °C the reactor performance deteriorated due to VFA accumulation and disintegration of the granular sludge. Biomass concentration in the hybrid reactor increased with the rapid development of biofilm on the matrix. The biofilm also prevented the washout of biomass from the reactor and enhanced COD removal by approximately 3%. Collins et al. (2013) compared the performances of a hybrid EGSB with a conventional EGSB and an anaerobic filter (AF) for the treatment of simulated whey in psychrophilic conditions. The experimental results indicated that diluted and high strength whey could be treated with all reactors at satisfactory organic removal efficiencies. At 12 °C, the hybrid EGSB provided higher COD removal (95%) when operated at higher OLR (5-15 kg COD m-3 d-1)compared to lower OLR (0.5-1.5 kg COD m-3 d-1). On the other hand, the hybrid EGSB reactor had higher COD removal of 70% than the AF with 61% when treating high strength whey (10 g COD L-1) at 15 °C. The researchers indicated that the upper fixed-film section of the hybrid EGSB offered a polishing step for the degradation of acidified wastewater from the initial upflow-bed stages.

Zielinska et al. (2013) constructed a pilot-scale hybrid reactor having the properties of a UASB and an AF. The lower chamber of the hybrid reactor was full of suspended sludge while the biofilm was immobilized on polyethylene particles in the upper chamber and the reactor was operated in upflow mode. The study was carried out at two temperatures of 35 and 55 °C and two OLRs of 1 and 2 kg COD m-3 d-1. The researchers also compared the reactor performance with convection and microwave heating. Microwave heating stimulated the growth of highly diverse methanogenic community while thermophilic conditions caused changes in microbial community. It was reported that the presence of methanogens within the reactor was sensitive to changes in OLR while the highest biogas production was at lower OLRs. In mesophilic conditions, biogas production was almost 7-fold higher compared to thermophilic temperatures, while microwave heating provided higher biogas production and methane content in all conditions studied. At mesophilic temperature, increases in OLR resulted in reduction in COD removal and the highest COD removal was 76% at 2 kg COD m-3 d-1 at 55 ºC. Banu et al. (2008) operated a similar hybrid reactor for the treatment of dairy wastewater using plastic cut rings for biofilm attachment media. Organic loading was gradually increased from 8 to 20 kg COD m-3 d-1 and the highest reactor performance was at an OLR of 19.2 kg COD m-3 d-1. When the OLR was increased to 20 kg COD m-3 d-1, COD removal efficiency was less than 65% along with a decrease in methane production. The authors explained that the decrease in reactor performance at higher OLR was related to the reduction of methanogenic activity at low pH caused by VFA accumulation. They recommended installing a post-treatment step to meet discharge limits, and obtained 95% COD removal and 96% BOD with a solar photocatalytic reactor.

Conventional granule reactors are also modified to overcome operational problems such as biogas liberation and scum formation. Passeggi et al. (2012) modified a UASB to avoid the problems caused by the FOG content of dairy wastewater. The researchers installed a scum extraction device to remove accumulated oily scum under the hood and also provided out a lamella settler for the UASB effluent while settled solids were reintroduced periodically into the reactor. Thus, biomass wash out was prevented and the biomass content in the reactor was preserved. The modified reactor was operated without pH adjustment even though the pH of raw wastewater varied between 5.0 and 11.5, which led to a reduced use of chemicals during operation. Furthermore, the HRT in the modified reactor was reduced by 22% and the required total treatment volume was reduced by 40% compared to a conventional treatment system. The modified reactor also required less investment and operational costs but 13% less biogas was obtained due to the greater gas losses.

**5 Conclusions and recommendations**

In this review, dairy wastewater-treating anaerobic granular reactors were evaluated. Several reactor systems have been constructed for dairy wastewater treatment, and many different operational strategies have been developed to maximize methane production. Reactors were compared based on COD removal efficiencies and methane production performance. Among the individual reactor systems, the UASB reactor has been widely preferred for dairy wastewater treatment due to its simple construction, ease of operation and high performance. Research has mainly been conducted in mesophilic conditions and few reports are available at elevated temperatures. Studies at low temperatures provide promising results for organic removal and methane production; however, more work should be done to increase the performance of reactors. In recent work, most studies have been performed with hybrid systems combining the properties of granular and biofilm systems. Reports reveal that optimization of organic loading has the primary effect on successful performance of granular reactors. Finally, it can be concluded that further research should be conducted on current reactor technologies to enhance energy production and organics removal from dairy wastewater.

**6 Acknowledgements**

The authors thank to Yıldız Technical University Scientific Research Projects Coordination Department (Project Number: 2013-05-02-KAP08) and to the ERA-NET BBSRC (AmbiGAS, Project Number: BEN6-12-19, BB/L000024/1) for financial support.

**7 References**

Akila G and Chandra T S (2007) Performance of an UASB reactor treating synthetic wastewater at low-temperature using cold-adapted seed slurry. *Process Biochemistry* 42 466–471.

Alves M M, Vieira J A M, Pereira R M A, Pereira M A and Mota M (2001) Effect of lipids and oleic acid on biomass development in anaerobic fixed-bed reactors. Part I: Biofilm growth and activity. *[Water Research](http://www.sciencedirect.com/science/journal/00431354" \o "Go to Water Research on ScienceDirect)* **[35](http://www.sciencedirect.com/science/journal/00431354/35/1" \o "Go to table of contents for this volume/issue)** 255–263.

Arbeli Z, Brenner A, Abeliovich A (2006). Treatment of high-strength dairy wastewater in an anaerobic deep reservoir: Analysis of the methanogenic fermentation pathway and the rate-limiting step. Water Research **40** 3653-3659.

Bandara W M K R T W, Satoh H, Sasakawa M, Nakahara Y, Takahashi M and Okabe S (2011) Removal of residual dissolved methane gas in an upflow anaerobic sludge blanket reactor treating low-strength wastewater at low temperature with degassing membrane. *Water Research* **45** 3533-3540.

Banik G C, Ellis T G and Dague R R (1997) Structure and methanogenic activity of granules from an ASBR treating dilute wastewater at low temperatures. [*Water Science Technol*](http://www.sciencedirect.com/science/journal/02731223)*ogy* **[36](http://www.sciencedirect.com/science/journal/02731223/36/6" \o "Go to table of contents for this volume/issue)** 149–156.

Banik S, Bandyopadhyay S and Ganguly S (2003) Bioeffects of microwave––a brief review, [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* **87** 155-159.

Banu JR, Anandan S, Kaliappan S and Yeom I T (2008) Treatment of dairy wastewater using anaerobic and solar photocatalytic methods. *Solar Energy* **82** 812–819.

Belancon D, Fuzzato M, Gomes D R S, Cichello G C V, Pinho S, Ribeiro R and Tommaso G (2010) A comparison of two bench-scale anaerobic systems used for the treatment of dairy effluents. International Journal of Dairy Techology **63** 290-296.

Bialek K, Cysneiros D and O’Flaherty V (2013). Low-Temperature (10 C) anaerobic digestion of dilute dairy wastewater in an EGSB bioreactor: microbial community structure, population dynamics, and kinetics of methanogenic populations. *Archaea*,346171 1-10.

Blonskaja V and Vaalu T (2006) Investigation of different schemes for anaerobic treatment of food industry wastes in Estonia. [*Proceedings of the* Estonian *Academy of Sciences*](http://www.kirj.ee/14446/?tpl=1061&c_tpl=1064)**55** 14–28.

Bodik I, Herdova B and Drtil M (2002) The use of upflow anaerobic filter andAnSBR for wastewater treatment at ambient temperature. *Water Research* **36** 1084–1088.

Borja R and Banks C J (1994) Kinetics of an upflow anaerobic sludge blanket reactor treating ice-cream wastewater. *Environment Technology* **15** 219-232.

Buntner D, Sanchez A S and Garrido JM (2011) Three stages MBR (methanogenic, aerobic bioﬁlm and membrane ﬁltration) for the treatment of low-strength wastewaters. Water Science Technology **64**, 397-402.

Buntner D, Sánchez A and Garrido J M (2013) Feasibility of combined UASB and MBR system in dairy wastewater treatment at ambient temperatures. *Chemical Engineering Journal* **230** 475–481.

Cammarota M C, Teixeira GA and Freire D M G (2001) Enzymatic pre-hydrolysis and anaerobic degradation of wastewaters with high fat contents. *Biotechnoly Letters* **23** 1591–1595.

Cayless SM, Marques D M L M and Lester J N (1990) A study of the effects of methanol in start-up of UASB reactors. [*Biology Waste*](http://www.sciencedirect.com/science/journal/02697483)*water* **[31](http://www.sciencedirect.com/science/journal/02697483/31/2" \o "Go to table of contents for this volume/issue)**123–135.

Chu L B, Yang F L and Zhang X W (2005) Anaerobic treatment of domestic wastewater in a membrane-coupled expended granular sludge bed (EGSB) reactor under moderate to low temperature. [*Process Biochemistry*](http://www.sciencedirect.com/science/journal/13595113) **40** 1063-1070.

Collins G, McHugh S, Connaughton S, Enright A M, KearneyA, Scully C, Mahony T, Madden P and Oflaherty V (2013) New low-temperature applications of anaerobic wastewater treatment. Journal of *Environmental Science Health, Part A: Toxic/Hazard. Subs. Environ. Eng.* **41** 881-895.

Córdoba P R, Francese A P and Siñeriz F (1995). Improved performance of a hybrid design over an anaerobic filter for the treatment of dairy industry wastewater at laboratory scale. Journal of fermentation and bioengineering, **79** 270-272.

Couras C S, Louros V L, Grilo A M, Leitão J H, Capela M I, Arroja L M and Nadais M H (2014). Effects of operational shocks on key microbial populations for biogas production in UASB (Upflow Anaerobic Sludge Blanket) reactors. *Energy* **73** 866-874.

Danalewich J R, Papagiannis T G, Belye R L, Tumbleson M E, Raskin L (1998). Characterization of dairy waste streams, current treatment practices, and potential for biological nutrient removal *Water Research* **32** 3555-3568.

Debik E and Coskun T (2009) Use of the static granular bed reactor (SGBR) with anaerobic sludge to treat poultry slaughterhouse wastewater and kinetic modelling. *Bioresource Technol* **100** 2777-2782.

Del-Pozo R, Diez V and Beltran S (2000) Anaerobic pre-treatment of slaughterhouse wastewater using fixed-film reactors. [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* **[71](http://www.sciencedirect.com/science/journal/09608524/71/2" \o "Go to table of contents for this volume/issue)** 143–149.

Demirel B, Yenigun O and Onay T T (2005). Anaerobic treatment of dairy wastewaters: a review. *Process Biochemistry* **40** 2583-2595.

Demirel B, Orok M, Hot E, Erki S, Albukrek M and Onay T T (2013) Recovery of biogas as a source of renewable energy from ice-cream production residues and wastewater. *Environmental Technology* **34** 2099–2104.

Diamantis V I, Kapagiannidisd A G, Ntougias S, Tataki V, Melidis P and Aivasidis A (2014). Two-stage CSTR–UASB digestion enables superior and alkali addition-free cheese whey treatment. *Biochemical Engineering Journal* **84** 45-52.

Dugba P N and Zhang R (1999) Treatment of dairy wastewater with two-stage anaerobic sequencing batch reactor systems—thermophilic versus mesophilic operations. *Bioresource Technology* **68** 225–233.

Erguder T H, Tezel U, Guven E and Demirer G N (2001) Anaerobic biotransformation and methane generation potential of cheese whey in batch and UASB reactors. [*Waste Manage*ment](http://www.sciencedirect.com/science/journal/0956053X) **21** 643-650.

Evans E A and Ellis T G (2005). Industrial wastewater treatment with the static granular bed reactor versus the UASB, [Proceedings of the Water Environment Federation](http://www.ingentaconnect.com/content/wef/wefproc), WEFTEC 2005: Session 21 through Session 30 , 2219-2231.

Evans E A and Ellis T G (2010). Experimental validation of the static granular bed reactor for industrial waste anaerobic treatment. *Journal of Environmental Engineering*, **136** 1139-1146.

Faye B and Konuspayeva G (2012) The sustainability challenge to the dairy sector – The growing importance of non-cattle milk production worldwide. [*International Dairy J*](http://www.sciencedirect.com/science/journal/09586946)*ournal* **24** 50-56.

Fuzzato M C, Adorno M A T, Pinho S C, Ribeiro R and Tommaso G (2009) Simplified mathematical model for an anaerobic sequencing batch biofilm reactor treating lipid-rich wastewater subject to rising organic loading rates. Environmental Engineering Science **26** 1197-1206.

Ganesh P S, Ramasamy E V, Gajalakshmi S, Sanjeevi R and Abbasi S A (2007). Studies on treatment of low-strength effluents by UASB reactor and its application to dairy industry wash waters. *Indian Journal* Biotechnology 234-238.

Gavala H N, Kopsinis H, Skiadas I V, Stamatelatou K and Lyberatos G (1999) Treatment of dairy wastewater using an upflow anaerobic sludge blanket reactor. *Journal of Agricultural Engineering Research* **73** 59-63.

Ghally A E, Ramkumar D R, Sadaka S S and Rochon J D (2000) Effect of reseeding and pH control on the performance of a two-stage mesophilic anaerobic digester operating on acid cheese whey. *Canadian Agricultural Engineering* **42849** 173-183.

Goodwin J A S, Wase D A J and Forster C F (1990). Anaerobic digestion of ice-cream wastewaters using the UASB process. [*Biological Waste*](http://www.sciencedirect.com/science/journal/02697483)*water* **32** 125-144.

Gutierrez J L R, Encina P A G and Fdz-Polanco F (1991) Anaerobic treatment of cheese-production wastewater using a UASB reactor. [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* **[37](http://www.sciencedirect.com/science/journal/09608524/37/3" \o "Go to table of contents for this volume/issue)**271–276.

Haridas A, Surech S, Chitra K R and Manilal V B (2005). The Buoyant filter reactor: a high-rate anaerobic reactor for complex wastewater—process dynamics with dairy effluent. *Water Research* **39** 993–1004.

Hawkes F R, Rozzi A, Black K, Guwy A, Hawkes D L (1992) The stability of anaerobic digesters operating on a food-processing wastewater. *Water Science and Technology* **25** 73–82.

Hawkes F R, Donnely T and Anderson G K (1995). Comparative performance of anaerobic digesters operating on ice-cream wastewater. [*Water Res*](http://www.sciencedirect.com/science/journal/00431354)*earch* **29**, 525–533.

Hwang S H, Hansen C L and Stevens D K (1992) Biokinetics of an upflow anaerobic sludge blanket reactor treating whey permeate. [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* 223–230.

Ibrahim S S, Latiff A A A and Daud A (2013) Preliminary study: Treatment of food industrial wastewater using two-phase anaerobic treatments. International *Journal of Integrated Engineering*, **5**,1-7.

Ince O (1998), Performance of a two-phase anaerobic digestion system when treating dairy wastewater. *Water Research* **32** 2707-2713.

Janczukowicz W, Zielinski M and Debowski M (2008) Biodegradability evaluation of dairy effluents originated in selected sections of dairy production. *Bioresource Technology*  **99** 4199–4205.

Kalyuzhnyi S V, Martinez E P and Martinez J P (1997) Anaerobic treatment of high-strength cheese whey wastewaters in laboratory and pilot uasb-reactors. *Bioresource Technology* **60** 59-65.

Karadag D, Koroglu O E, Ozkaya B, Cakmakci M, Heaven S and Banks C (2014) A review on fermentative hydrogen production from dairy industry wastewater, *Journal of Chemical Technology Biotechnology* **89** 1627-1636.

Kim S H, Han S K and Shin H S (2004) Two-phase anaerobic treatment system for fat-containing wastewater. *Journal of Chemical Technology Biotechnology* **79**, 63–71.

Kim S H, Kim L and Shin H S (2006) Enhanced lipid degradation in upflow anaerobic sludge blanket reactor by integration with acidogenic reactor. WEFTEC 2006, USA, October 21-25.

Kundu K, Bergmann I, Hahnke S, Klocke M, Sharma S and Sreekrishnan T R (2013) Carbon source - A strong determinant of microbial community structure and performance of an anaerobic reactor. *Journal of Biotechnology* **168** 616-624.

Kushwaha, J.P., 2013. A review on sugar industry wastewater: sources, treatment technologies, and reuse. Desalination Water Treatment 1-10.

Kwiatkowsk A C, Zielinski M and Jaranowsk P (2012) Microwave radiation and reactor design influence microbial communities during methane fermentation, [Journal of Industrial Microbiology and Biotechnol](http://link.springer.com/journal/10295)ogy **39** 1397-1405.

Latif M A, Ghufran R, Wahid Z A and Ahmad A (2011). Integrated application of upflow anaerobic sludge blanket reactor for the treatment of wastewaters. *Water research*, **45** 4683-4699.

Leal M C M R, Freire D M G, Cammarota C and Santanna G L (2006) Effect of enzymatic hydrolysis on anaerobic treatment of dairy wastewater. *Process Biochemistry* **41**1173–1178.

Leitão R C, Van Haandel A C, Zeeman G, Lettinga G (2006). The effects of operational and environmental variations on anaerobic wastewater treatment systems: a review. *Bioresource Technology*, **97**1105-1118.

Lim S J and Kim, T H (2014). Applicability and trends of anaerobic granular sludge treatment processes. *Biomass and Bioenergy* **60**, 189-202.

Lim S J, Kim T H (2014) Applicability and trends of anaerobic granular sludge treatment processes, [*Biomass Bioenergy*](http://www.sciencedirect.com/science/journal/09619534) [**60**](http://www.sciencedirect.com/science/journal/09619534/60/supp/C) 189-202.

Lopez-Fiuza J, Buys B, Mosquera-Corral A, Omila F and Mendez R (2002) Toxic effects exerted on methanogenic, nitrifying and denitrifying bacteria by chemicals used in a milk analysis laboratory. *Enzyme Microbial Technology* **31** 976–985.

Luostarinen S A and Rintala J A (2005) Anaerobic on-site treatment of black water and dairy parlour wastewater in UASB-septic tanks at low temperatures. *Water Research* **39** 436–448.

Matsumoto E M, Osako M S, Pinho S C, Tommaso G, Gomes T M and Ribeiro R (2012). Treatment of wastewater from dairy plants using Anaerobic Sequencing Batch Reactor (ASBR) following by Aerobic Sequencing Batch Reactor (SBR) aiming the removal of organic matter and nitrification. Water Practice & Technology **7** 1-11.

McHugh S, OReilly C, Mahony T, Colleran E, Olaherty V and [Colleran](http://link.springer.com/search?facet-author=%22Emer+Colleran%22) E (2003) Anaerobic granular sludge bioreactor technology. *R[ev. Environmental Science Biotechnology](http://link.springer.com/journal/11157)* **2** 225-245.

McHugh S, Collins G and O’Flaherty V (2006) Long-term, high-rate anaerobic biological treatment of whey wastewaters at psychrophilic temperatures. *Bioresource Technol*ogy **97** 1669–1678.

Mockaitis G, Ratusznei S M, Rodrigues A D, Zaiat M and Foresti E (2006) Anaerobic whey treatment by a stirred sequencing batch reactor (ASBR):effects of organic loading and supplemented alkalinity. *Journal of Environmental Management* **79** 198–206.

Monroy H O, Vázquez M F, Derramadero J C and Guyot J P (1995). Anaerobic-aerobic treatment of cheese wastewater with national technology in Mexico: The case of “El Sauz”. Water Science and Technology, **32** 149-156.

Murray W D and van den Berg A L (1981) Effects of nickel, cobalt, and molybdenum on performance of methanogenic fixed-film reactors. *Applied Environmental Microbiology* **42** 502-505.

Nadais H, Capela I, Arroja L and Duarte A (2005) Optimum cycle time for intermittent UASB reactors treating dairy wastewater, *Water Research* **39** 1511–1518.

Nadais M H, Capila M I and Aroja L M (2006) Intermittent vs continuous operation of upflow anaerobic sludge bed reactors for dairy wastewater and related microbial changes. *Water Science Technology* **54** 103–109.

Nadais H, Barbosa M, Capela I, Arrjoja L, Ramos C G, Grilo A, Sousa S A and Leitao J H (2011) Enhancing wastewater degradation and biogas production by intermittent operation of UASB reactors, *Energy* **36** 2164-2168.

Najafpour G D, Hashemiyeh B A, Asadi M and Ghasemi M B (2008) Biological treatment of dairy wastewater in an upflow anaerobic sludge-fixed film reactor. *American-Eurasian Journal of Agricultural & Environmental Sciences***4** 251-257.

Ndon U J and Dague R R (1997a) Effects of temperature and hydraulic retention time on anaerobic sequencing batch reactor treatment of low-strength wastewater. [*Water Res*](http://www.sciencedirect.com/science/journal/00431354)*earch* **[31](http://www.sciencedirect.com/science/journal/00431354/31/10" \o "Go to table of contents for this volume/issue)** 2455–2466.

Ndon U J, Dague R R (1997b) Ambient temperature treatment of low strength wastewater using anaerobic sequencing batch reactor. *Biotechnology Letters* **19** 319-324.

Neves L, Oliveira R and Alves M M (2009) Co-digestion of cow manure, food waste and intermittent input of fat. [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* **100** 1957-1962.

Oh J H, Park J and Ellis T G (2014). Performance of on-site pilot static granular bed reactor (SGBR) for treating dairy processing wastewater and chemical oxygen demand balance modeling under different operational conditions. Bioprocess and biosystems engineering, 1-11.

Omil F, Garrido J M, Arrojo B and Mendez R (2003) Anaerobic filter reactor performance for the treatment of complex dairy wastewater at industrial scale. *Water Research* **37** 4099–4108.

Ozgun H, Dereli R K, Ersahin M E, Kinaci C, Spanjers H and van Lier J B (2013) A review of anaerobic membrane bioreactors for municipal wastewater treatment: Integration options, limitations and expectations, [*Separation and Purification Technol*](http://www.sciencedirect.com/science/journal/13835866)*ogy* [**118**](http://www.sciencedirect.com/science/journal/13835866/118/supp/C) 89–104.

Ozturk I, Eroglu V, Ubay G and Demir I (1993) Hybrid upflow anaerobic sludge blanket reactor (HUASBR) treatment of dairy effluents. *Water Science Technology* **28** 77–85.

Palatsi J, Laureni M V, Flotats X, Nielsen H B and Angelidaki I (2009) Strategies for recovering inhibition caused by long chain fatty acids on anaerobic thermophilic biogas reactors. *Bioresource Technology* **100** 4588–4596.

Park J, Oh J H, Evans E A, Lally M F, Hobson K L and Ellis T G (2012) Industrial wastewater treatment by on-site pilot static granular bed reactor (SGBR). *Water Practice and Technology* 7 1-11.

Passeggi M, López I and Borzacconi L (2012) Modified UASB reactor for dairy industry wastewater: performance indicators and comparison with the traditional approach. *Journal of Cleaner Production* **26** 90-94.

Pereira M A, Cavaleiro A J, Mota M and Alves M M (2003) Accumulation of long chain fatty acids onto anaerobic sludge under steady state and shock loading conditions: effect on acetogenic and methanogenic activity. *Water Science and Technology* **48** 33–40.

Prazeres AR, CarvalhoF and Rivas J (2012) Cheese whey management: A review. [*Journal Environmental Manage*](http://www.sciencedirect.com/science/journal/03014797)*ment* **110** 48-68.

Pretti A A, Moreno J G, Santana R S S, Pinho S C, Tommaso G and Ribeiro R (2011). Effect of configuration of biomass on the behaviour of anaerobic batch reactors in pilot-scale treating dairy wastewater. In 11th International Congress on Engineering and Food.

Rajagopal R, Saady N M C, Torrijos M, Thanikal J V and Hung Y T (2013) Sustainable agro-food industrial wastewater treatment using high rate anaerobic process. *Water* **5** 292-311.

Rajeshwari K V, Balakrishnan M, Kansal A, Lata K and Kishore V V N (2000) State-of-the-art of anaerobic digestion technology for industrial wastewater treatment. *Renewable & Sustainable Energy* **4** 135-156.

Ramasamy E V, Gajalakshmi S, Sanjeevi R, Jithesh M N and Abbas S A (2004) Feasibility studies on the treatment of dairy wastewaters with upflow anaerobic sludge blanket reactors. [*Bioresource Technol*](http://www.sciencedirect.com/science/journal/09608524)*ogy* **[93](http://www.sciencedirect.com/science/journal/09608524/93/2" \o "Go to table of contents for this volume/issue)**209–212.

Rebac S, Van Lier J B, Lens P, Stams A J M, Dekkers F T M, Swinkels K and Lettinga G (1999) Psychrophilic anaerobic treatment of low strength wastewaters. *Water Science and Technology* **39** 203–210.

Satoh H, MiurY, Tsushim I and Okabe S (2007a) Layered structure of bacterial and archaeal communities and their in situ activities in anaerobic granules. *Applied and Environmental Microbiology* **73** 7300-7307.

Satoh H, Miura Y, Tsushima I and Okabe S (2007b). Anaerobic granules communities and their in situ Activities in anaerobic granules, *Applied and Environmental Microbiology* **73** 7300-7307.

Shuizhou K, Shi Z, and Herbert HP Fang (2005) Applications of two-phase anaerobic degradation in industrial wastewater treatment, *International Journal of Environment and Pollution* **23**, 65-80.

Strydom J P, Britz T Z, Mostert J F (1997) Two-phase anaerobic digestion of three different dairy effluents using a hybrid reactor. *WaterSa* 23 151-156.

Strydom J P, Mostert J F and Britz T J (1995). Anaerobic treatment of a synthetic dairy effluent using a hybrid digester. *Water SA*, *21* 125-130.

Tauseef S M, Abbasi T and Abbasi S A (2013) Energy recovery from wastewaters with high-rate anaerobic digesters. *Renewable & Sustainable Energy Reviews* **1** 704, 741.

Tawfik A, Sobhey M and Badawy M (2008) Treatment of a combined dairy and domestic wastewater in an upflow anaerobic sludge blanket (UASB) reactor followed by activated sludge (AS system), *Desalination* **227** 167–177.

Traversi D, Bonetta S, Degan R, Villa S, Porfido A, Bellero M, Carraro E, Gilli G (2013). Environmental Advances Due to the Integration of Food Industries and Anaerobic Digestion for Biogas Production: Perspectives of the Italian Milk and Dairy Product Sector. *Bioenergy Research* **6** 851–863.

Turkdogan F I, Park J, Evans E A and Ellis T G (2013) Evaluation of pretreatment using UASB and SGBR reactors for pulp and paper plants wastewater treatment. [*Water, Air and Soil Pollut*](http://link.springer.com/journal/11270)*ion* **224** 1512.

Vlyssides A, Barampouti E M and Mai S (2007) Effect of ferrous ion on the biological activity in a UASB reactor. Mathematical modeling and veriﬁcation. *Biotechnology and Bioengineering* **96** 853–861.

Vlyssides A, Barampouti E M and Mai S (2008) Granulation mechanism of a UASB reactor supplemented with iron. *Anaerobe*  **14** 275–279.

Vlyssides A, Barampouti E M and Mai S (2009) Influence of ferrous iron on the granularity of a UASB reactor, *Chemical Engineering Journal* **146** 49–56.

Vlyssides A G, Tsimas E S, Barampouti E M P and Mai S T (2012) Anaerobic digestion of cheese dairy wastewater following chemical oxidation, *Biosystem Engineering* **113**, 253-258.

Yan J Q, Lo K V and Liao P H (1988) Methane production from cheese whey. *Biomass* **17** 185-202.

Yan J Q, Lo K V and Liao P H (1989) Anaerobic digestion of cheese whey using upflow anaerobic sludge blanket reactor. *Biological Waste* **27** 289-305.

Yan J Q, Lo K V and Pinder K L (1993). Instability caused by high strength of cheese whey in a UASB reactor. *Biotechnology and Bioengineering*, **41**700-706.

Yang G and Anderson G K (1993) [Effects of wastewater composition on stability of UASB](http://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9372(1993)119:5(958)), *Journal of Environmental Engineering* **119** 958-977.

Yenigun O and Demirel B (2013) Ammonia inhibition in anaerobic digestion: A review, [*Process Biochemistry*](http://www.sciencedirect.com/science/journal/13595113) [**48**](http://www.sciencedirect.com/science/journal/13595113/48/5) 901–911.

Yu H Q, Fang H H P, (2000) Thermophilic acidification of dairy wastewater. Applied Microbiology and Biotechnology 54 439-444.

Yu H Q and Fang H H P (2001) Inhibition on acidogenesis of dairy wastewater by zinc and copper. *Environmental Technology* **22** 1459-1465.

Yu H Q, Herbert H P and Gu G W (2002) Comparative performance of mesophilic and thermophilic acidogenic upflow reactors. *Process Biochemistry* **38** 447-454.

Zielinska M, Cydzik-Kwiatkowska A, Zielinski M and Debowski M (2013) Impact of temperature, microwave radiation and organic loading rate on methanogenic community and biogas production during fermentation of dairy wastewater, *Bioresource Technology* **129** 308–314.

**Tables**

Table 1 Dairy industry wastewater characteristics

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Wastewater  Source | pH | COD  (g L-1) | Solids  (g L-1) | Nitrogen  (mg L-1) | Phosphorus  (mg L-1) | FOG  (g L-1) | Reference |
| Cheese production | 6.7 | 2.93 | 2.75 (TS) | 36 (TN) | 21 | 0.294 | Gutierrez et al., 1991 |
| Ice-cream | 6.96 | 4.94 | 1.1 (TSS) | NA | NA | NA | Hawkes et al. 1995 |
| Cheese production | 5.5-9.5 | 1.0-7.5 | 0.5-2.5 | NA | NA | NA | Monroy et al., 1995 |
| Whey | 4.3-8.7 | 5.4-77.3 | 3.9-58.9 (TS) | 500-5600 (TN) | NA | 0.4-5.7 | Kalyuzhnyi et al., 1997 |
| Butter production | 5.8 | 1.91 | 1.72 | NA | NA | NA | Strydom et al., 1997 |
| Cheddar cheese production | 6.2 | 7.62 | 6.34 | 106 (TKN) | 20 | NA | Danalewich et al., 1998 |
| Milk and cream bottling plant | 8-11 | 2-6 | 0.3-1.0 (TSS) | 50-60 | 20-50 | 0.3-0.5 | Ince, 1998 |
| Whey | 3.92 | 74.5 | 9.38 (SS) | 145.6 (TN) | 124 | NA | Erguder et al., 2001 |
| Dairy wastewater | NA | 18 | 7.18 (TSS) | 329 (TKN) | 637 | 4.89 | Arbeli et al., 2006 |
| Whey | 5.5-6.6 | 50-70 | 55-65 TS | NA | NA | NA | Najafpour et al., 2008 |
| Simulated milk | 6.5-7.0 | 0.15-11 | NA | 75-550 (TN) | 12-88 | NA | Vlyssides et al., 2008 |

NA:Not available; SS:Suspended solid; TS:Total solid; TN=Total Nitrogen; TKN=Total Kjhedahl  Nitrogen; FOG:Fats, Oil and Grease

**Table 2** Comparison of anaerobic granular reactors treating dairy wastewater

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Reactor | Wastewater | Temp.  (°C ) | pH | HRT  (day) | OLR  (kg COD m3d-1) | Inf. COD  (g L-1) | COD removal  (%) | CH4 yield  (m3 CH4 kg-1 COD) | Reference |
| UASB | Whey |  | 7-8 | 2-5 | 10.4-24.6 | 42.7-55.65 | 91.9-97.0 | 0.424 | Erguder et al., 2001 |
| UASB | Whey | 35 | 6.6-7.3 | 6-40 | 1.5-7.3 | 12-60 | 79-99 | NA | Gavala et al., 1999 |
| UASB | Cheese production | 35 | 7.3 | 0.07-0.5 | 4.6-31 | 1.7-2.34 | 88-97 | 0.29-0.33 | Gutierrez et al. 1991 |
| UASB | Whey | 20-35 | 7.0-7.5 | 2.3-12.8 | 3-28.5 | 5-77 | 90-99 | NA | Kalyuzhnyi et al., 1997 |
| UASB | Simulated dairy | 30 | NA | 0.13-0.5 | 2.4-13.5 | 1.44 | 37-96.3 | NA | Ramasamy et al., 2004 |
| UASB | Washing wastewater | 30 | 6.8-7.4 | 0.25-0.75 | 0.80-9.60 | 0.6-2.0 | 75-85 | NA | Ganesh et al., 2007 |
| Hybrid | Simulated milk | 37 | NA | 0.75-5 | 2.22-31 | 10-77.5 | 78 | 0.27 | Kundu et al., 2013 |
| Hybrid | Dairy | 12-20 | 7-8 | 0.75-2 | 5-13.3 | 5-10 | 52.3-91.9 | NA | McHugh et al., 2006 |
| Hybrid | Whey | 36 | 6.5 | 1.5-2 | 7.9-45.42 | 50-70 | 77-97.5 | NA | Najafpour et al., 2008 |
| Hybrid | Simulated dairy | 35, 55 | NA | 1 | 1,2 | 1,2 | 64-76 | 0.037-0.245 | Zielinska et al., 2013 |
| Hybrid | Butter production | 35 | 7.8 |  | 0.97 | 1.84 | 91 | 0.287 | Strydom et al., 1997 |