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State-of-the-art of anaerobic digestion technology for industrial wastewater treatment

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Abstract

Anaerobic digestion is the most suitable option for the treatment of high strength organic effluents. The presence of biodegradable components in the effluents coupled with the advantages of anaerobic process over other treatment methods makes it an attractive option. This paper reviews the suitability and the status of development of anaerobic reactors for the digestion of selected organic effluents from sugar and distillery, pulp and paper, slaughterhouse and dairy units. In addition, modifications in the existing reactor designs for improving the efficiency of digestion has also been suggested. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Anaerobic digestion; Reactors; Effluents; Sugar; Distillery; Pulp and paper; Slaughterhouse; Dairy

1. Introduction

There is a growing interest in alternate energy sources as a result of increased demand for energy coupled with a rise in the cost of available fuels. Rapid industrialization has resulted in the generation of a large quantity of effluents with

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Nomenclature

AAFEB	Anaerobic Attached — Film Expanded — Bed Reactor
AFB	Anaerobic Fluidized Bed
AnRBC	Anaerobic Rotating Biological Contact Reactor
BOD	Biological Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
COD	Chemical Oxygen Demand
DSFFR	Downflow Stationary Fixed Film Reactor
DUHR	Downflow Upflow Hybrid Reactor
EGSB	Expanded Granular Sludge Bed
FBR	Fluidized Bed Reactor
GAC	Granular Activated Carbon
HRT	Hydraulic Retention Time
MCRT	Mean Cell Retention Time
OLR	Organic Loading Rate
RBC	Rotating Biological Contactor
SDFA	Semicontinuous Digester with Flocculant Addition
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
UFFLR	Upflow Fixed Film Loop Reactor
USSB	Upflow Staged Sludge Bed
VFA	Volatile Fatty Acids

high organic contents, which if treated suitably, can result in a perpetual source of energy. In spite of the fact that there is a negative environmental impact associated with industrialization, the effect can be minimized and energy can be tapped by means of anaerobic digestion of the wastewater. In recent years, considerable attention has been paid towards the development of reactors for anaerobic treatment of wastes leading to the conversion of organic molecules into biogas. These reactors, known as second generation reactors or high rate digesters, can handle wastes at a high organic loading rate of 24 kgCOD/m^3 day and high upflow velocity of 2–3 m/h at a low hydraulic retention time [1]. However, the treatment efficiencies of these reactors are sensitive to parameters like wastewater composition, especially the concentration of various ions [2,3] and presence of toxic compounds such as phenol [4]. The temperature and pH are also known to affect the performance of the reactor by affecting the degree of acidification of the effluent and the product formation [5].

An improvement in the efficiency of anaerobic digestion can be brought about by either suitably modifying the existing digester design or by incorporating appropriate advanced operating techniques. Thus, a plug flow reactor or USSB reactor is found to be superior to the conventional processes due to low concentrations of VFA in the effluent, a high degree of sludge retention and stable reactor performance [6]. Another common problem encountered in the industrial anaerobic plants is biomass washout. This can be addressed, for instance, by the use of membranes coupled with the anaerobic digester for biomass retention [7].

This paper reviews the development of various reactors for the treatment of high strength wastewaters from selected industries viz distillery, pulp and paper, dairy and slaughterhouse. The emphasis is on identifying the critical factors affecting performance so that the reactor efficiency can be improved by maintaining optimal operating conditions. Further, an assessment of the suitability of specific reactor types for different wastewaters is presented and the possible modifications in the existing process to enhance the system efficiency is discussed.

2. High rate anaerobic reactors

All modern high rate biomethanation processes are based on the concept of retaining high viable biomass by some mode of bacterial sludge immobilization. These are achieved by one of the following methods [8].

- Formation of highly settleable sludge aggregates combined with gas separation and sludge settling, e.g. upflow anaerobic sludge blanket reactor and anaerobic baffled reactor.
- Bacterial attachment to high density particulate carrier materials, e.g. fluidized bed reactors and anaerobic expanded bed reactors.
- Entrapment of sludge aggregates between packing material supplied to the reactor, e.g. downflow anaerobic filter and upflow anaerobic filter.

Table 1 summarizes some of the important features of these reactors which are briefly discussed below.

2.1. Fixed film reactor

In stationary fixed film reactors (Fig. 1), the reactor has a biofilm support structure (media) such as activated carbon, PVC (polyvinyl chloride) supports, hard rock particles or ceramic rings for biomass immobilization. The wastewater is distributed from above/below the media. Fixed film reactors offer the advantages of simplicity of construction, elimination of mechanical mixing, better stability at higher loading rates, and capability to withstand large toxic shock loads [11] and organic shock loads [12]. The reactors can recover very quickly after a period of starvation [11]. The main limitation of this design is that the reactor volume is relatively high compared to other high rate processes due to the volume occupied by the media. Another constraint is clogging of the reactor due to increase in biofilm thickness and/or high suspended solids concentration in the wastewater.

Table 1
Characteristics of different reactor types [9,10]

Anaerobic reactor type	Start up period	Channelling effect	Effluent recycle	Gas solid separation device	Carrier packing	Typical loading rates (kgCOD/ m^3 day)	HRT (d)
CSTR	–	Not present	Not required	Not required	Not essential	0.25–3	10–60
Contact	–	Non-existent	Not required	Not required	Not essential	0.25–4	12–15
UASB	4–16	Low	Not required	Essential	Not essential	10–30	0.5–7
Anaerobic filter	3–4	High	Not required	Beneficial	Essential	1–40	0.5–12
AAFEB	3–4	Less	Required	Not required	Essential	1–50	0.2–5
AFB	3–4	Non-existent	Required	Beneficial	Essential	1–100	0.2–5

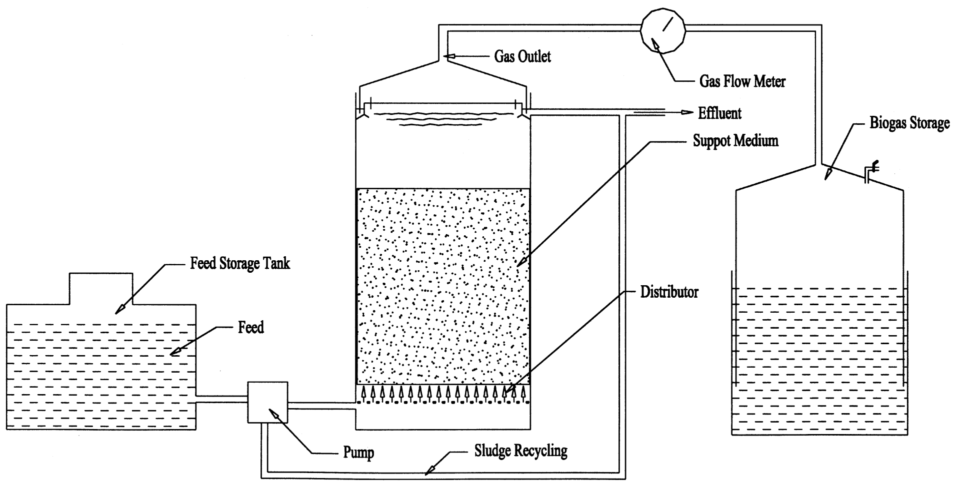

Fig. 1. Fixed film reactor.

2.2. Upflow anaerobic sludge blanket reactor

UASB technology is being used extensively for effluents from different sources such as distilleries, food processing units, tanneries and municipal wastewater. The active biomass in the form of sludge granules is retained in the reactor by direct settling for achieving high MCRT thereby achieving highly cost-effective designs. A major advantage is that the technology has comparatively less investment requirements when compared to an anaerobic filter or a fluidized bed system. Among notable disadvantages, it has a long start-up period along with the requirement for a sufficient amount of granular seed sludge for faster startup. Moreover, significant wash-out of sludge during the initial phase of the process is likely and the reactor needs skilled operation.

A UASB reactor (Fig. 2) essentially consists of gas–solids separator (to retain the anaerobic sludge within the reactor), an influent distribution system and effluent draw off facilities. Effluent recycle (to fluidize the sludge bed) is not necessary as sufficient contact between wastewater and sludge is guaranteed even at low organic loads with the influent distribution system [13]. Also, significantly higher loading rates can be accommodated in granular sludge UASB reactors as compared to flocculent sludge bed reactors. In the latter, the presence of poorly degraded or non-biodegradable suspended matter in the wastewater results in an irreversible sharp drop in the specific methanogenic activity because the dispersed solids are trapped in the sludge. Moreover, any significant granulation does not occur under these conditions. The maximum loading potential of such a flocculent sludge bed system is in the range of 1–4 kgCOD/m^3 day [14].

Yet another high rate digester, EGSB, is a modified form of UASB in which a slightly higher superficial liquid velocity is applied (5–10 m/h as compared to 3 m/

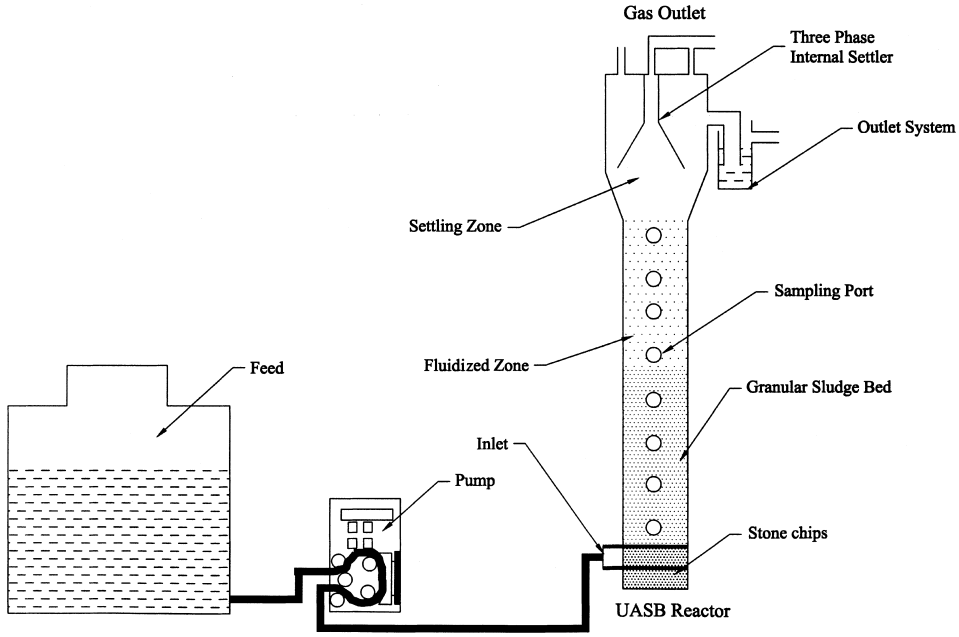

Fig. 2. Upflow anaerobic sludge blanket reactor (UASB) reactor.

h for soluble wastewater and 1–1.25 m/h for partially soluble wastewater in an UASB) [1]. Because of the higher upflow velocities, mainly granular sludge will be retained in an EGSB system, whereas a significant part of granular sludge bed will be in an expanded or possibly even in a fluidized state in the higher regions of the bed. As a result, the contact between the wastewater and sludge is excellent. Moreover, the transport of substrate into the sludge aggregates is much better as compared to situations where the mixing intensity is much lower [1]. The maximum achievable loading rate in EGSB is slightly higher than that of an UASB system, especially for a low strength VFA containing wastewater and at lower ambient temperatures.

2.3. Anaerobic fluidized bed reactor

In the anaerobic fluidized bed (Fig. 3), the media for bacterial attachment and growth is kept in the fluidized state by drag forces exerted by the upflowing wastewater. The media used are small particle size sand, activated carbon, etc. Under fluidized state, each media provides a large surface area for biofilm formation and growth. It enables the attainment of high reactor biomass hold-up and promotes system efficiency and stability. This provides an opportunity for higher organic loading rates and greater resistance to inhibitors. Fluidized bed technology is more effective than anaerobic filter technology as it favors the

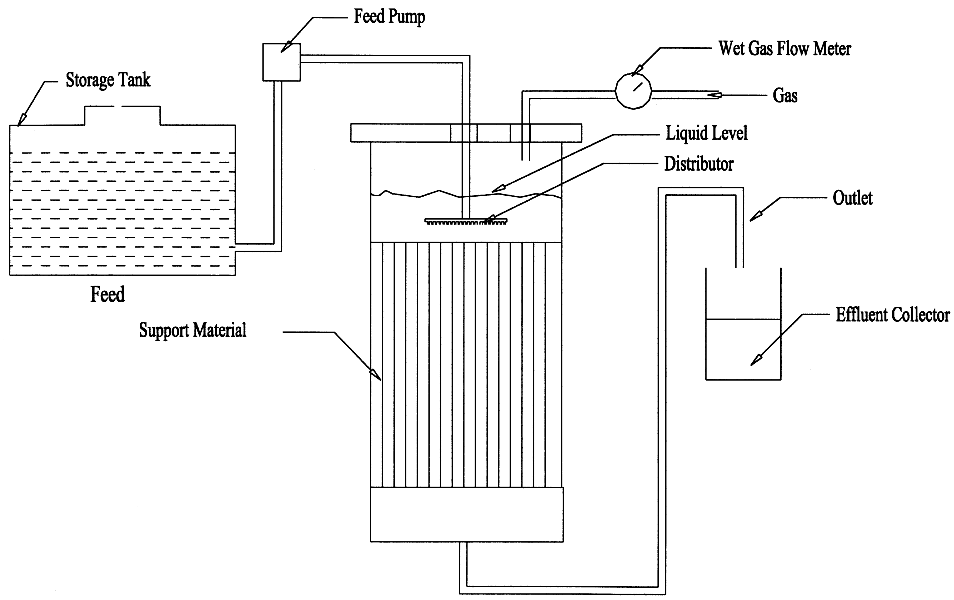

Fig. 3. Anaerobic fluidized bed reactor.

transport of microbial cells from the bulk to the surface and thus enhances the contact between the microorganisms and the substrate [15]. These reactors have several advantages over anaerobic filters such as elimination of bed clogging, a low hydraulic head loss combined with better hydraulic circulation [16] and a greater surface area per unit of reactor volume. Finally, the capital cost is lower due to reduced reactor volumes. However, the recycling of effluent may be necessary to achieve bed expansion as in the case of expanded bed reactor. In the expanded bed design, microorganisms are attached to an inert support medium such as sand, gravel or plastics as in fluidized bed reactor. However, the diameter of the particles is slightly bigger as compared to that used in fluidized beds. The principle used for the expansion is also similar to that for the fluidized bed, i.e. by a high upflow velocity and recycling.

3. Control of anaerobic digestion

The anaerobic digestion process is affected significantly by the operating conditions. As the process involves the formation of volatile acids, it is important that the rate of reaction be such that there is no accumulation of acids, which would result in the failure of the digester.

This, in turn, is governed by the loading rate and the influent strength. Temperature and pH are other important variables as the methane producing bacteria are sensitive to these as well.

3.1. Effect of temperature

Anaerobic digestion is strongly influenced by temperature and can be grouped under one of the following categories [17]: psychrophilic (0–20°C), mesophilic (20–42°C) and thermophilic (42–75°C). The details of the bacterial processes in all the three temperature ranges are well established though a large section of the reported work deals with mesophilic operation. Changes in temperature are well resisted by anaerobic bacteria, as long as they do not exceed the upper limit as defined by the temperature at which the decay rate begins to exceed the growth rate. In the mesophilic range, the bacterial activity and growth decreases by one half for each 10°C drop below 35°C [17]. Thus, for a given degree of digestion to be attained, the lower the temperature, the longer is the digestion time.

The effect of temperature on the first stage of the digestion process (hydrolysis and acidogenesis) is not very significant, as among the mixed population there are always some bacteria which have their optimum within the range concerned. The second and third stages of decomposition can only be performed by certain specialized microorganisms (acetogenic and methanogenic bacteria) and thus, these are much more sensitive towards temperature change [3]. However, an important characteristic of anaerobic bacteria is that their decay rate is very low at temperatures below 15°C. Thus, it is possible to preserve the anaerobic sludge for long periods without losing much of its activity. This is especially useful in the anaerobic treatment of wastewater from seasonal industries such as sugar mills.

3.2. Effect of pH

Anaerobic reactions are highly pH dependent. The optimal pH range for methane producing bacteria is 6.8–7.2 while for acid-forming bacteria, a more acid pH is desirable [3]. The pH of an anaerobic system is typically maintained between methanogenic limits to prevent the predominance of the acid-forming bacteria, which may cause VFA accumulation. It is essential that the reactor contents provide enough buffer capacity to neutralize any eventual VFA accumulation, and thus prevent build-up of localized acid zones in the digester. In general, sodium bicarbonate is used for supplementing the alkalinity since it is the only chemical, which gently shifts the equilibrium to the desired value without disturbing the physical and chemical balance of the fragile microbial population [17].

3.3. Effect of nutrients

The presence of ions in the feed is a critical parameter since it affects the granulation process and stability of reactors like UASB. The bacteria in the anaerobic digestion process requires micronutrients and trace elements such as nitrogen, phosphorous, sulphur, potassium, calcium, magnesium, iron, nickel, cobalt, zinc, manganese and copper for optimum growth. Although these elements are needed in extremely low concentrations, the lack of these nutrients has an adverse effect upon the microbial growth and performance. Methane forming bacteria have relatively high internal concentrations of iron, nickel and cobalt. These elements may not be present in sufficient concentrations in wastewater streams from the processing of one single agroindustrial product like corn or potatoes or the wastewater derived from condensates. In such cases, the wastewater has to be supplemented with the trace elements prior to treatment [17]. The required optimum C:N:P ratio for enhanced yield of methane has been reported to be 100:2.5:0.5 [18]. The minimum concentration of macro and micronutrients can be calculated based on the biodegradable COD concentration of the wastewater, cell yield and nutrient concentration in bacterial cells [17]. Table 2 presents the elemental composition of the methane forming bacteria in the bacterial consortium. In general, the nutrient concentration in the influent should be adjusted to a value equal to twice the minimal nutrient concentration required in order to ensure that there is a small excess in the nutrients needed.

3.4. Effect of organic loading rate

In anaerobic wastewater treatment, loading rate plays an important role. In the case of nonattached biomass reactors, where the hydraulic retention time is long, overloading results in biomass washout. This, in turn, leads to process failure. Fixed film, expanded and fluidized bed reactors can withstand higher organic loading rate. Even if there is a shockload resulting in failure, the system is rapidly restored to normal. In comparison to a CSTR system, fixed film and other attached biomass reactors have better stability. Moreover, high degree of COD reduction is achieved even at high loading rates at a short hydraulic retention time. Table 1 gives the recommended COD loading rates with various reactor configurations. Anaerobic fluidized bed appears to withstand maximum loading rate compared to other high rate reactors.

Table 2
The elemental composition of methane bacteria [17]

Macronutrients		Micronutrient	
Element	Concentration (mg/kg)	Element	Concentration (mg/kg)
N	65,000	Fe	1800
P	15,000	Ni	100
K	10,000	Co	75
S	10,000	Mo	60
Ca	4000	Zn	60
Mg	3000	Mn	20
		Cu	10

4. Anaerobic digestion of selected high strength wastewaters

4.1. Slaughterhouse and meat packing

Wastewater from a slaughterhouse arises from different steps of the slaughtering process such as washing of animals, bleeding out, skinning, cleaning of animal bodies, cleaning of rooms, etc. The wastewater contains blood, particles of skin and meat, excrements and other pollutants. Typical characteristics of wastewater from slaughterhouses are given in Table 3.

Anaerobic ponds are commonly used to achieve a high degree of BOD reduction in slaughterhouse wastewater. However, this suffers from the disadvantage of odour generation from the ponds thus making the development of alternate designs very essential. Anaerobic contact, upflow anaerobic sludge blanket, and anaerobic filter reactors have been tried for slaughterhouse wastes. All these have a higher OLR ranging from 5 to 40 kgCOD/m^3 day [20]. The high rate anaerobic treatment systems such as UASB and fixed bed reactors are less popular for slaughterhouse wastes due to the presence of high fat oil and suspended matters in the influent. This affects the performance and efficiency of the treatment systems. Also, because of relatively low BOD, high rate systems which function better for higher BOD concentrations are not appropriate. Table 4 summarizes the performance data of digestors used for the treatment of slaughterhouse wastewater.

The anaerobic contact reactor appears to be more suitable compared to UASB as the latter is constrained by the lack of formation of granules and there is also loss of sludge due to high fat concentrations. Hence, a pre-treatment step for removal of fats and suspended solids becomes essential if an UASB is to be used. However, for a low COD load, the more efficient UASB appears to result in a high COD reduction. In a study on fish meal processing wastewater, treatment in an upflow anaerobic filter was carried out after a centrifugation step to remove the solids [21]. The maximum applied OLR was 5 kgCOD/m^3 day. An increase in the recycling ratio from 1:10 to 1:5 resulted in the accumulation of VFA, ammonia and VSS.

An anaerobic fluidized bed reactor of 1.2 l capacity has been tested in the

Table 3
Characteristics of the wastewater from the slaughterhouses [19]

Parameter	Concentration (g/l)
pH	6.8–7.8
COD	5.2–11.4
TSS	0.57–1.69
Phosphorus	0.007–0.0283
Ammoniacal nitrogen	0.019–0.074
Protein	3.25–7.86

Table 4
Treatment systems for slaughterhouse wastes [20]

Reactor	Capacity (m^3)	OLR (kgCOD/m^3 day)	Reduction (%)
UASB (granular)	33	11	85
UASB (flocculated)	10	5	80–89
Anaerobic filter	21	2.3	85
Anaerobic contact	11,120	3	92.6

laboratory for wastewater from slaughterhouse with a COD concentration upto 4500 mg/l [22]. More than 94% COD reduction could be obtained for an OLR of 27 kgCOD/m^3 day. It was reported that due to the presence of unused acids in the reactor, it was essential to maintain the desired alkalinity. A two-stage system for treating high strength wastewater from an abattoir has been tried by Rivera et al. [23]. The system consists of an anaerobic digester followed by an artificially constructed wetland that utilizes the rootzone of hydrophytes planted in a gravel substrate. The treatment efficiency was high with COD and BOD reduction of 87.4% and 88.5%, respectively. The suspended solids removal was 89% and 99% of the faecal coliforms was eliminated. The treated effluent is being used for irrigation of plants and land. The importance of anaerobic pre-treatment for reducing part of the organic carbon prior to aerobic treatment is also emphasized in the studies carried out by Keller et al. [24].

4.2. Cheese whey and dairy

The liquid waste in a dairy originates from manufacturing process, utilities and service sections. The various sources of waste generation from a dairy are spilled milk, spoiled milk, skimmed milk, whey, wash water from milk cans, equipment, bottles and floor washing. Whey is the most difficult high strength waste product of cheese manufacture. This contains a proportion of the milk proteins, water-soluble vitamins and mineral salts. The characteristics of the dairy wastewater and cheese whey are given in Table 5.

The treatment of cheese whey wastewaters by anaerobic degradation is constrained by the drop in pH that inhibits further conversion of acids to methane. This can be taken care of with buffering action in a hybrid reactor, which is not possible in an UASB reactor. However, with proper startup, UASB reactors can also cope with cheese whey wastewaters at low pH of 4 even at high OLR of 6.5 kgCOD/m^3 day [27]. A high treatment efficiency with 90% COD reduction has been achieved in laboratory and pilot scale reactors at both mesophilic and submesophilic temperatures with a maximum OLR of 28.5 kgCOD/m^3 day and 9.5 kgCOD/m^3 day, respectively. At ambient temperature, in a 10.7 m^3 reactor, a treatment efficiency of 95% with maximum OLR of 6.5 kgCOD/m^3 day has been reported. In a study on treatment of dairy wastewater with low COD of 2.05 g/l, very high OLR of 31 kgCOD/m^3 day was possible at a

Table 5
Characteristics of dairy effluent [25,26]

Components	Concentration (mg/l)		
	Dairy	Whey	Whey permeate
pH	5.6–8	–	–
COD	1120–3360	75,000	50,000
BOD	320–1750	–	–
Lactose	–	40,000	40,000
Propionate (mmol/l)	–	5	4
K (mmol/l)	–	38	36
Ca (mmol/l)	–	7	2
Suspended solids	28–1900	–	–
Total solid	–	50,000	42,000
Oil and grease	68–240	–	–

HRT of 1.7 h [28]. The COD reduction of 95% dropped to 70–80% with increase in OLR to 45 kgCOD/m^3 day. This is a common problem encountered with cheese whey, that as the substrate loading is increased, the acidogenic region extends into the methanogenic. This makes the entire region acidic, ultimately resulting in the failure of the reactor [29,30]. Thus, two-stage process becomes essential for improving the biogas production rate and methane yield. The effect of temperature and pH control on biogas production and COD reduction has been summarized in the studies carried out by Ghaly [31] (Table 6). It is clear that buffering is needed initially for maintaining the pH but at a later stage, the stability improves with a mature microbial population.

A hybrid reactor was used with a pre-acidification step to treat three different dairy effluents — cheese, fresh milk and butter wastewaters [32]. The COD reduction was found to be 91–97% for OLR ranging from 0.97 to 2.82 kgCOD/m^3 day. The methane yield was 0.287–0.359 m^3/kgCOD removed. Apart from the hybrid reactor other alternate reactor types have also been tried for the treatment of dairy-based wastewaters (Table 7). In addition, a 450 m^3 novel multiplate anaerobic reactor has been tried for cheese whey effluent in a cheese factory in Canada [45]. The COD of the effluent ranged between 20 and 37 kg/m^3. The OLR fluctuated between 9 and 15 kgCOD/m^3 day. The maximum efficiency in terms of COD removal was 92% and average methane production rate was 4 m^3/m^3 day.

In the study carried out by Guitonas et al. [46], a fixed bed reactor of 10.7 l volume with cells immobilized on rice straw was used for the treatment of milk based synthetic organic waste. The advantage of the system was the lower adaptation time with change in the OLR.

4.3. Sugar and distillery waste

The manufacturing process in a distillery involves dilution of molasses with water followed by fermentation. The product is then distilled to obtain rectified

Table 6
Effect of temperature and pH control on the treatment of cheese whey

Temperature (°C)	HRT (days)	Biogas production (l/day)		COD reduction (%)		Methane (%)	
		pH control	Without pH control	With pH control	Without pH control	With pH control	Without pH control
25	10	83.70	27.90	28.2	0.5	70.8	20.2
	15	71.30	24.80	32.2	6.1	71.0	20.1
	20	60.45	20.15	34.9	8.7	70.9	20.2
35	10	156.50	58.90	28.5	10.2	70.8	20.1
	15	139.50	49.60	33.6	13.4	70.9	20.2
	20	125.50	41.85	36.0	15.6	70.9	20.2

Table 7
Performance study of different types of anaerobic reactors for the treatment of cheese whey and dairy wastewater

Reactor	HRT (days)	Influent conc. (g/l)	OLR (kgCOD/m^3 day)	COD reduction (%)	Reference
UASB	2.3–11.6	5–77	1–28.5	95–99	27
UASB	5.4–6.8	47–55	7–9.5	90–94	27
UASB	3.3–12.8	16–50	1–6.7	90–95	27
UASB (dairy)	1.7 h	2.05	31	90	28
UASB (cheese whey)	5	4.5–38.1	–	–	29
2-stage (cheese whey)	10–20	72.2	–	36	31
UFFLR	5	79	14	95	33
DSFFR	5	13	2.6	88	34
FBR	0.4	7	7.7	90	35
FBR	0.1–0.4	0.8–10	6–40	63–87	36
AAFEB	0.6–0.7	5–15	8.2–22	61–92	37
AnRBC	5	64	10.2	76	38
SDFA	–	69.8	16.1	99	39
UASB	1.5	11	7.1	94	40
UASB	5	5–28.7	0.9–6	97–99	41
DUHR	7	68	10	97	42
UASB (whey permeate)	5–0.4	10.4	–	–	43
An-RBC (cheese whey and dairy manure)	–	–	–	46	44

spirit or neutral alcohol. The distillation process results in the generation of a strong organic effluent (Table 8). The source of other wastes is from floor washings, recovery units of yeast and other byproducts. The sugar manufacturing process broadly involves the extraction, clarification and concentration of sugarcane juice. Finally, the concentrated juice is crystallized and dried. The manufacturing process primarily produces bagasse and press mud as waste. In addition, the process generates wastewater, with the typical characteristics as summarized in Table 8.

In the case of effluent from a cane sugar factory, the buffering capacity is low and the alkali requirement is high leading to high operational cost. An increased growth rate of the methanogens at higher temperatures makes the thermophilic anaerobic digestion process a suitable alternative to mesophilic digestion. With synthetic sugar waste in a 5.75 l UASB reactor, more than 85% conversion of glucose could be achieved upto 49.3 kgCOD/m^3 day within a period of 92 days. The maximum methane production was 14.1 m^3 CH_4/m^3 day. The granules were well formed and the sludge was maintained in the granular state, starting from 48 days after the feeding was started [48].

A diphasic fixed film reactor with GAC as support media has been used for treatment of distillery spentwash. Though the COD reduction is only 67.1%, the gas yield is high at 0.45 m^3/kgCOD removed with a methane content of 70%. The HRT is reported to be 4 days corresponding to an OLR of 21.3 kgCOD/m^3 day. In the acid phase, the optimum condition is at an HRT of 1.2 days, corresponding to an OLR of 54–72 kgCOD/m^3 day [47].

For the treatment of stillage from sugarcane molasses using an UASB reactor, the dilution had a significant effect on the loading rate. In a 100 l reactor for stillages with COD ranging from 35 to 100 g/l, an OLR of 24 kgCOD/m^3 day resulted in 75% COD removal and a biogas production of 9 l/l day with methane content of 58%. Feeding with undiluted stillage resulted in a tremendous increase

Table 8
Characteristics of sugar cane and distillery effluents [26,47]

Components	Concentration (mg/l)	
	Sugar cane	Distillery
pH	8.14	3.8–4.4
COD	276	70,000–98,000
BOD	54	45,000–60,000
Na	4.05	150–200
K	1.64	5000–12,000
Fe	10.83	–
Cu	0.72	–
Mn	0.06	–
Total solids	–	60,000–90,000
Total suspended solids	–	2000–14,000

in the concentrations of acetic and propionic acids, thus affecting the stability of the reactor [49]. Malt whisky distillery potale, a liquid waste product from the malt whisky industry, treated in a laboratory scale UASB reactor [50] indicated the importance of dilution and pH control in attaining a high COD reduction. There is normally a rise in the pH due to ammonia production during the process of digestion. The maximum loading rate for a stable operation was 15 kgCOD/m^3 day at a retention time of 2.1 days. The feasibility of UASB for distillery wastewater at a high temperature of 55°C was investigated by Harada et al. [51]. In a 140 l capacity UASB reactor for an influent concentration of 10 gCOD/l, an OLR of 28 kgCOD/m^3 day could be attained. However, the COD reduction was very low at approximately 65%. Application of UASB for the treatment of simulated distillery waste was studied in a 29 l UASB reactor by Rao et al. [52]. The maximum organic loading rate achieved was 47 kgCOD/m^3 day. The minimum HRT was 4.9 h and a methane yield of 0.29 m^3 CH_4/kgCOD removed was obtained. A short period of 10 days was sufficient for the reactor to recover after a shutdown for one month. The performance of the reactor is currently being studied with the effluent from a local distillery. Thermophilic anaerobic digestion for vinasse, the wastewater of alcohol distilleries has also been carried out with the adapted sludge [53]. After adaptation of the sludge for 4 months, an organic load of 86.4 kgCOD/m^3 day could be accommodated. The methane generation rate is 26 m^3 CH_4/m^3 day. The high concentration of vinasse was found to affect the size of the sludge granules though the overall reactor performance was not affected. In certain cases, supplementing the effluent with the nutrients such as nitrogen and phosphorus have proved effective. In the case of anaerobic digestion of wood ethanol stillage using an UASB reactor [54], supplementation with nitrogen, phosphorus and alkalinity resulted in a stable reactor performance at an organic loading rate of 16 kgCOD/m^3 day. The soluble COD and BOD removal was 86% and 93%, respectively. However, the colour removal was just 40%. The methane yield at this loading rate was 0.302 m^3 CH_4/kgCOD removed.

4.4. Pulp and paper

The manufacture of pulp and paper broadly involves the following steps:

1. Pulping process, involving the pulping of cellulosic materials by mechanical, chemical or chemo-mechanical means.
2. Bleaching process, wherein the colour on pulp due to lignin is removed by using chlorine or other oxidising agents.
3. Paper making involving the blending of pulp with water in desired proportion and further processing in paper machine.

In the pulp and paper industry, there are various points of wastewater generation. Some wastewater results from leaks and spills from digester. Pulp washing and bleaching gives wastewaters of various characteristics depending on the bleaching sequence. Bleaching section results in wastewater and chlorolignins. Wastewater is also generated from paper machine section, caustic chlorine manufacture and black liquor recovery. There are variations in the COD, inhibitors and the degradability depending upon the source of the wastewaters (Table 9).

Chlorine bleaching effluents are not suitable for anaerobic treatment due to their low biodegradability and presence of toxic substances that affects the methanogens. Some of the alternate chlorine bleaching processes currently being adopted are elemental chlorine free and total chlorine free bleaching. In the study by Vidal et al. [56], the toxicity and degradability of the above bleaching effluents were compared with that of chlorine bleaching effluents. The effect of the elemental chlorine free and chlorine bleaching effluents were similar but the total chlorine free effluents were found to be less toxic. This can be attributed to the fact that apart from elemental chlorine, other components such as wood resin compounds produced during extraction processes are toxic. The COD reduction was found to be 75% in case of effluent generated from total chlorine free bleaching process whereas the reduction is 67% for chlorine bleaching effluent. The application of biological granular activated carbon process for the treatment of bleach plant effluent is evident from the study carried out by Jackson-Moss et al. [57]. It was observed that 50% of the COD and colour could be removed and that there was improvement in the adsorptive capacity due to microbial activity.

A laboratory scale study was carried out by Korczak et al. [58], for the anaerobic treatment of effluents from acid hydrolysis of wood from sulfate cellulose production and from the sulfite cellulose fibers washing. The efficiency was about 80% in terms of COD reduction and the methane production was 0.34 m^3/kgCOD removed for the high strength effluent (63,000 mg/l) from acid hydrolysis. However, for the effluent from cellulose washings, the COD reduction was only 20–30% and the methane yield was 0.27–0.36 m^3/kgCOD removed. This was due to the fact that the effluent contained refractory compounds such as lignin derivatives, resins and tannins apart from sugars. An attempt has been made to purify the thermomechanical pulp effluent by combining a nanofiltration method to anaerobic digestion [59]. This novel process was found to result in a

Table 9
Characteristics of wastewater generated from pulp and paper industry [55]

Wastewater	COD (mg/l)	Degradation (%)	Inhibitors
Wet debarking	1300–4100	44–78	Tannins, resin acids
Pulping			
Thermomechanical	1000–5600	60–87	Resin acids
Chemithermomechanical	2500–13,000	40–60	Resin acids, fatty acids, sulfur
Chemical pulping			
Sulfite condensate	7000	–	Sulfur, ammonia
Chlorine bleaching	900–2000	30–50	Chlorinated phenols, resin acids
Sulfite spent liquor	120,000–220,000	–	
Kraft condensate	1000–33,600	83–92	Sulfur, resin acids, fatty acids, terpenes
Sulfite condensate	7500–50,000	50–90	Sulfur, organic sulfur

very clean water that could be reused in the water circulation system of the plant. In the case of paper and pulp mill effluent, a four stage treatment process — pre-treatment, anaerobic treatment using an UASB, aerobic treatment and tertiary flotation was found to be successful. This had resulted in an average COD reduction of 82% [60].

Table 10 summarizes the use of different types of reactors for the treatment of paper and pulp effluent.

5. Factors governing reactor choice

A technology is acceptable to an industry if it requires less capital, less land area and is more reliable when compared to the other well established options. For an anaerobic digestion system, this translates into the process being able to run at high organic and hydraulic loading rates with minimum operation and maintenance requirements. To choose the most appropriate reactor type for a particular application, it is essential to conduct a systematic evaluation of different reactor configurations with the wastewater stream.

The organic and hydraulic loading potential of a reactor depends on three factors viz

- Amount of active biomass that can be retained by a reactor per unit volume.
- Contact opportunity between the retained biomass and the incoming wastewater.
- Diffusion of substrate within the biomass.

With these considerations, granular sludge UASB reactor stands out distinctively as the best choice with the only limitations being the tendency of granules to float and shearing of granules at high loading rates. These constraints are also valid to a lesser degree for attached biomass reactors (such as fixed film, fluidized bed and rotary biological contactors). In addition, due to the space occupied by the media, the attached biomass reactors possess comparatively lower capacity for biomass

Table 10
Comparison of treatment efficiency of various reactors for wastewaters from different streams of paper and pulp

Reactor type	Wastewater	COD removed (%)	OLR
UASB	Debarking	40	40 kgCOD/m^3 day
Fluidized bed	Debarking	50 (BOD)	0.66 m^3/ m^3 day
UASB	Mechanical pulping	–	
Mesophilic	Thermomechanical	60–70	12–31 kgCOD/m^3 day
55–70°C		60	80 and 13 kgCOD/m^3 day
	Chemithermomechanical	60	4 and 20 kgCOD/m^3 day
		35–55	4.7–22 kgCOD/m^3 day
Contact process	Sulfite condensate	30–50	5 kgCOD/m^3 day

retention per unit volume of the reactor. The latter depends on the film thickness, which would be the highest in a fluidized bed reactor due to large surface area available for biomass attachment. Also, there is better contact between the biomass and the incoming wastewater in both fluidized bed and EGSB systems. However, due to the high upflow velocity, the substrate diffusion in the biomass is limited in these configurations.

Based on these factors, it appears that the maximum achievable loading rates with soluble wastewater would decrease in the following sequence: UASB > EGSB > fluidized bed reactor > anaerobic filter. The capital cost of the reactors and the land area requirements, therefore, follows the same order.

The digester operation and maintenance requirements are minimum if the process is fairly stable towards fluctuations in wastewater characteristics and changes in environmental conditions. Susceptibility of the process depends on the potential utilization of the reactor and thus a system operating near maximum loading conditions is more sensitive. Based on the comparisons of various reactor types, the following order can be recommended for reactor choice:

Parameters	Rating
Operating skills	Fixed film < UASB < RBC < fluidized bed
Energy consumption	UASB < fixed film < EGSB < fluidized bed < RBC
Capital cost, land requirement, O&M	RBC < fixed film < UASB < EGSB < fluidized bed

6. Conclusions

Although most of the high rate reactors have proved their applicability for different high strength wastewaters over a range of organic loading rates, there exists certain differences in the preference of a particular type of digester over others in terms of various factors such as requirement of pre-treatment, dilution, control of operating conditions, etc. In the case of slaughterhouse wastewater, an anaerobic contact reactor can be used without pre-treatment whereas for the usage of high rate digester such as UASB, a pre-treatment step for removal of the suspended solids and fats is essential prior to anaerobic treatment. Two phase digestion with pH and temperature control results in a higher biogas production rate with cheese whey wastewater digestion. Distillery effluent due to its high strength appears to be having maximum potential in comparison to other effluents. UASB and fixed film reactors are more commonly used for distillery effluent due to their ability to withstand high OLR. An aerobic post-treatment is necessary to attain the permissible COD and BOD level before discharge. Due to the generation of wastewater from various sections of pulp and paper industry, there are variations in the composition and the treatability of effluents. Hence, it is preferable to treat the effluents from each section separately depending on their biodegradability and suitability to the digestion process rather than treating the combined effluent. Advanced methods such as coupling of reactors for suitable pre-treatment and post-treatment can result in complete treatment of the effluents with the acceptable limits.

It is clear from the review that there are no governing factors that dictates the suitability of any particular reactor design for a specific effluent. By suitable modifications in the reactor designs and by altering the effluent characteristics, the existing high rate digesters can be accommodated for treatment of organic effluents. However, based on the characteristics of the different reactors such as efficiency based on loading rate and COD reduction, biomass retention and other factors like cost, operation and maintenance requirements, UASB and fixed film configurations appear to be the most suitable.

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