

UPGRADED ANAEROBIC REACTORS FOR HIGH & LOW STRENGTH WASTEWATERS-A REVIEW AND ANALYSIS (2000-2018)

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Abstract: Anaerobic digestion is the most feasible option for treating organic wastewaters due to the presence of biodegradable organic content. Anaerobic treatment systems have paved their way in research being most energy efficient, lesser sludge production and biogas production for energy recovery. This paper reviews the status of research in anaerobic digestion process from the year 2000. Types of high rate anaerobic reactors, their efficiencies were discussed. Factors affecting the anaerobic digestion process along with the application of reactors were reviewed.

Indexing terms: Anaerobic digestion; Upgraded anaerobic reactors; wastewater treatment

1. Introduction

Anaerobic wastewater treatment has evolved into a competitive technology in last few decades. Agricultural and industrial wastes having very high biodegradable organic content are most suitable for anaerobic digestion. Moreover conventional aerobic treatment systems being highly sludge productive, energy intensive and release greenhouse gases which increases the life cycle cost. Thereby anaerobic treatment systems have paved their way in research being most energy efficient, lesser sludge production and biogas production. Anaerobic waste treatment is the most widely opted technology for wastewater treatment [1-3]. The applications of anaerobic technology include both high and low strength industrial wastewaters. The anaerobic degradation results in breakdown of complex organic compounds into methane and carbon dioxide. This involves four different groups of microbial consortia, namely hydrolytic, acidogenic, acetogenic and methanogenic bacteria [4]. The biogas produced by anaerobic digestion is an odourless, colourless and non-poisonous gas. A series of reactions happen during anaerobic process, which require cooperative action of above said microbial consortia. Fig-1 represents the flow chart of reactions happening inside the anaerobic reactors [5].

This review is focussed on technological advancements in the field of anaerobic reactors for wastewater treatment from the year 2000 onwards. This study analyzes the type of high rate anaerobic reactors evolved, their research trend, application of the reactors, factors affecting the reactors, kinetics and microbial consortium analysis.

2. Research Trend:

Research trend has been studied on Scopus. Fig-1 represents the number of papers published from the year 2000. Research has been advancing linearly from year 2000 in anaerobic digestion. There were around 14000 documents regarding anaerobic digestion. Fig-2 represents the country wise research trend. India is found to be in the third place in research of anaerobic digestion.

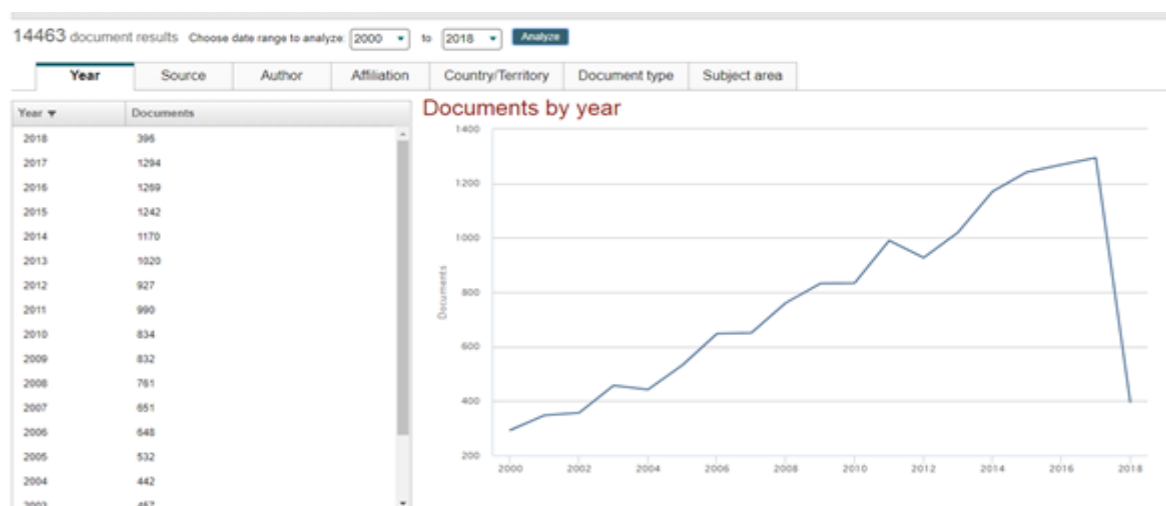


Fig-1: Research trend (Source:Scopus)

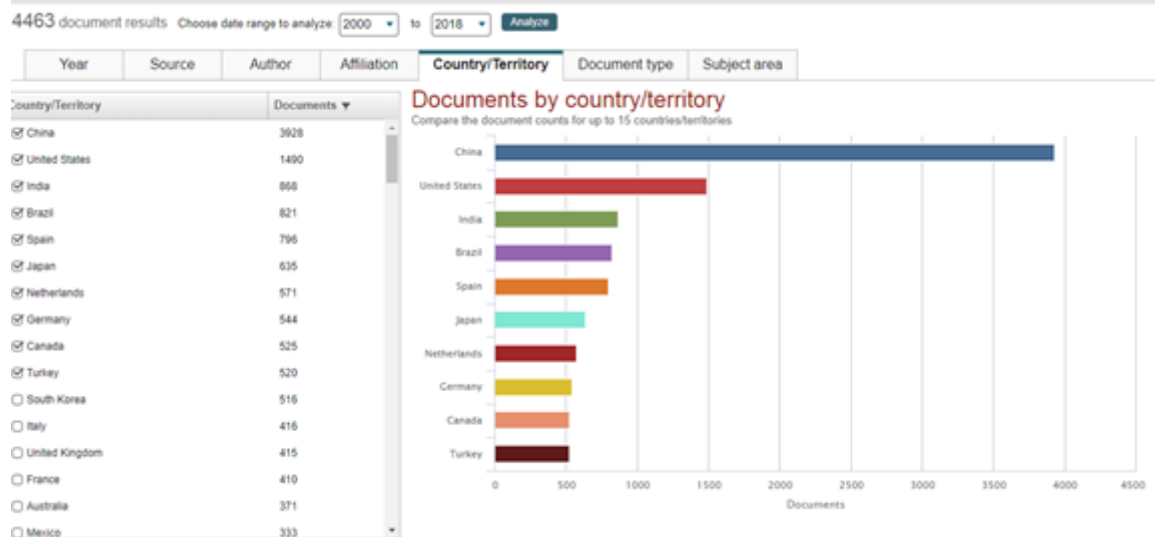


Fig-2: Country wise research trend (Source:Scopus)

3. Type of Anaerobic reactors:

There are various anaerobic reactors evolved from past two decades. The following are the few high rate anaerobic reactors.

3.1. Upflow Anaerobic Sludge Blanket reactors (UASB):

The Upflow Anaerobic Sludge Blanket (UASB) reactor technology is considered to be the step forward in the development and application of anaerobic high-rate technology for industrial wastewater. Initial first trials being in early seventies, the system became rapidly popular in agro and food industries [1]. This is the most extensively used anaerobic reactors in the world. Nearly 80% of the world's anaerobic reactors are estimated to be UASB [2]. The UASB reactor works with the principle of sludge bed being expanded, when wastewater flows vertically upwards, inside the reactor. Microbial consortia attached to the sludge particles acts upon the wastewater. Quality of bio film formed supported by the sludge particles, and the ease in the contact between microbes and the wastewater acts as governing factors for this technology. Granular sludge of appropriate particle size, particle density, and microfilm characteristics enhances the reactor performance in terms of the rate as well as the degree of wastewater treatment, making it high rate reactor [2]. There are various types of granules inside the reactor. Young granules are found to be black, small and compact having active cells, grey granules containing starving and dead cells and brown granules which are found to be bigger with loose amorphous structure and represent older granules. These types of granules enable selection of appropriate seed sludge for start-up of reactors. *Firmicutes* (as *Nitrospira* and *Deferribacteres* were found to be the predominant *Bacteria*. The methanogenic *Archaea* identified were *Methanosaeta concilii*, *Methanosarcina mazei*, and *Methanospirillum* spp. [3]. Fig-3 represents a UASB reactor [6]. It includes a gas separator cum hood, sludge bed with granules and baffles. Effluent enters from the bottom and treated effluent comes out from the top.

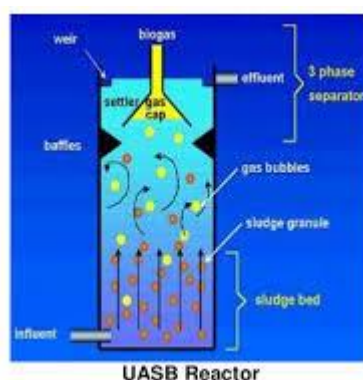


Fig-3: UASB reactor

UASB reactors were applied for various wastewaters. A simulated wastewater containing sizing agents, azo dyes, salts and other additives was treated using a lab-scale UASB reactor. COD removal efficiency was found to be 80% with HRT of 100 hours, however color removal efficiency was found to be above 90% at 100hrs and 6hrs HRT [7]. UASB when applied in synthetic dairy wastewater, COD removals were found to be 90% for enzymatically hydrolyzed effluent and 82% for raw effluent [8]. Starch wastewater, treated with UASB reactor at hydraulic retention time (HRT) of 6 hours and organic loading rate (OLR) 4 g COD/L•d achieved 81.1-98.7% removal of COD [9]. Lab scale hybrid upflow anaerobic sludge blanket reactor was applied for synthetic pharmaceutical wastewater. Acclimatization of microbes and maximum loading capacity were studied. It was found that at OLR of 8 kg COD/m³ d, COD removal efficiency was found to be 70% after acclimatization [10]. The average percentage reduction in

COD in a opaque beer manufacturing full scale plant was 57% and the the total and settleable solids were also reduced by 50 and 90%, respectively [11]. Phenol was effectively degraded in UASB with 40 hours of HRT and an OLR of 0.9g-COD/L/d. The maximum specific methanogenic activity (SMA) was found to be 0.09g CH₄-COD/g-volatile suspended solids(VSS)/d [4]. Microbial characteristics of UASB reactor were studied for paper mill wastewater, brewery wastewater and textile wastewater. Paper mill wastewater sludge has showed that Archaea were two-times more abundant in the microbial community of anaerobic sludge than Bacteria and also sulphate-reducing bacteria and syntrophic fatty acid-oxidizing microorganisms dominated the enrichments [12]. Methanothrix like bacteria were the dominant group in granules and they were reduced to cocci- shaped microorganisms after treatment of textile wastewater with UASB[13]. Anaerobic biofilms were studied for formation, structure and biodiversity in an UASB. The biofilm development can be roughly divided into three stages: an initial attachment phase (0–36 h) characterized by random adhesion of the cells to the surface; a consolidation phase (from 36 h to 2 weeks) defined by the appearance of micro colonies; and maturation phase (from 2 weeks to 2 months). Alpha proteo bacteria were dominant species of phyla. *Firmicutes*, *Bacteroidete*, and *Thermotogae* was also found in the granules [5].

3.2. Bi-phasic anaerobic reactor:

Bi-phasic anaerobic reactors are characterized by separation of acidogenic activity and methanogenic activity. This technology took its shape because of the limitations of a single reactor system, creating a problem in maintaining the delicate balance between these two groups of microorganisms. Prospects for the phased anaerobic treatment systems for wastewater is promising. The availability of various reactor designs, amenability of reactors for upgradation to achieve higher loading capacities, increased stability and great treatment efficiencies, made biphasic system popular in the market. Biphasic reactors have been applied for slaughterhouse wastewater, pulp and paper mill wastewater. Treatment efficiencies for COD removal were found to be above 85% in pulp and paper mill wastewater. [14,15].

3.3. Continuous stirred tank reactor:

Continuous stirred tank reactors are accommodated with a stirrer for proper mixing of effluent. Continuous stirred tank reactors have found its advantages in various applications in the last decade. Biological hydrogen production from carbohydrates using mixed cultures has been tried under mesophilic and thermophilic conditions. CSTR experiments suggest that thermophilic conditions combine high hydrogen production rate with low production of microbial mass, thus giving a high specific hydrogen production rate at 6 hours retention time [16,17]. Heavy metal removal using CSTR was studied, 90% removal of heavy metals was found at 8 weeks[18]. Microbial communities in a stirred tank reactor at mesophilic conditions were found to be the Firmicutes, which were the most abundant group, followed by the Chloroflexi and the Gamma-Proteobacteria. Actinobacteria, Bacteroidetes and Deferribacteres were the other bacterial groups detected. *Methanosaeta concilii* was the most representative species among the methanogens.[19]. CSTR have typical loading rates of 0.25-0.3kg COD/cu.m/d[20].

3.4. Fixed film reactors:

Fixed film reactors have the bio support media made of activated carbon, polyvinyl chloride supports or ceramic rings with biomass immobilization. The wastewaters are distributed from above or below the media. These reactors have advantage of better stability at higher organic loading rates, elimination of mechanical mixer there by reducing the cost and simple construction. Requirement of high reactor volumes and clogging/channelling are the limitations for this system [20]. Fixed film reactors have been used for slaughterhouse wastewater and winery wastewater treatment with average OLR of 0.77 kg COD/m³ d and 42 kg COD/m³ d respectively[21,22]

3.5. Fluidized bed reactors:

The anaerobic fluidized bed reactors have the media with bacterial attachment in fluidized state. The effluent enters from the bottom. Fluidized state provides the flexibility to have large surface area for biomass formation and growth, thereby increasing the stability of the system. This provides great capacity to with stand shock loads on the system [20]. Fluidized bed reactors have been used for removal of alkyl benzene sulfonate (LAS) with 48% removal efficiency. Proteobacteria and Synergistetes were identified in the samples [23]. COD removal efficiency was found to be 90% with OLR of 10 g COD/L d. Triturated polyethylene support has shown good removal efficiency. Reactor with extendsphere has shown excellent biologic behavior with OLR upto 70 g COD/L d[24].

3.6. Granular sludge bed reactor:

Granular bed reactor and expanded granular bed reactor are the modified form of UASB reactors. These offer high upflow velocities. This granular sludge is retained in the reactor for granular bed reactor and some other part will be in fluidized bed in expanded granular sludge bed reactor (EGSB). Organic loading rate is higher than UASB making it a high rate reactor. This works best for low strength wastewater [20]. Static granular bed reactors were used to treat poultry wastewater with 95% removal of COD. [26]. EGSB has been applied for domestic wastewater with upflow velocity more than 4m/h with effluent recirculation. This mixing intensity and sludge bed increases the performance of EGSB for low strength wastewater [25].

3.7. Membrane bioreactor:

Membrane bioreactors have taken a major place in anaerobic digestion system in the last decade. Table-1 represents the various type of membrane bioreactors studied. Hydraulic retention times of 8hrs to 60hrs have been studied in membrane bioreactors.

COD removal efficiencies were above 80% with anaerobic membrane bioreactors. Flux rates and transmembrane pressure have played an important role in membrane processes.

Table-1: Type of MBR

Type of membrane bioreactor	Membrane type	HRT	SRT	Performance	Methane gas yield	Reference
FO AnMBR	Forward osmosis membrane	-	-	Organic carbon removal-96%	0.21 L CH ₄ /g ₁ COD	27
IAFMBR		8hrs		COD removal - 75.8%	190 L CH ₄ /kgCOD	28
Submerged membrane bioreactor	Hollow fibre ultrafiltration membrane	20hrs	70days	COD removal:87%		29
Submerged membrane bioreactor	Hollow fibre ultrafiltration membrane		70days		53.6% methane recovery efficiency	30
An MBR	Polyether sulphone membrane	60hrs	50days	COD removal- 81-94%	0.136m ³ /kg COD.	31
An MBR	Tubular poly-tetrafluoroethylene (PTFE) microfiltration membrane			COD removal- 85%		32
Submerged membrane bioreactor	PES microfiltration membrane	8hrs	infinite	COD removal- 97%	0.056 L CH ₄ /g MLVSS d	33
Submerged membrane bioreactor	Side stream membrane filtration			COD removal- 90%	0.26LCH ₄ /g COD	34

3.8. Moving bed reactor:

Moving bed bioreactor processes are the biofilm processes where various carrier materials like polyurethane (PU) foam or biodegradable polymer polycarbonate (PCL) are used. This is a high rate processes with extremely compact reactors with total of 1 HRT is also possible. This type of reactors has applications in phosphorous and nitrogen removal along with BOD and COD removal. These reactors are extensively used for nitrification and de-nitrification for municipal and industrial wastewater [35, 36].

3.9. Anaerobic baffle filter reactor:

Anaerobic baffled reactors have baffles to separate the compartments where various reactions take place in different compartments. It is considered as UASB in series. Table-2 represents types of baffle reactors. Number of compartments tried was between 4 and 9. Bacteria in sludge granules rise inside the reactor due to upflow. Gas production is seen in each compartment with settlement. Major advantage of this system is separation of acidogenesis and methanogenesis, without implying high costs, as no mechanical mixing is required or moving parts are involved. Sludge generation is low with high SRT. Hydraulic retention times observed were found to be from 8hrs to 4 days. COD removal performance in these reactors were found to be above 80%.[37-43].

Table-2: Type of Anaerobic baffle filter

Type of filter	Anaerobic	Compartments	OLR(kgC OD/m ³)	HRT	Performance	Methane gas yield	Reference
ABR		4	1.2-6	-	COD-92-97%	-	37
ABR		3	-	48hrs	COD removal - 85%	-	38
Carrier Anaerobic baffled reactor(CABR)		6	-	48hrs	COD removal:79%		39
Combined ABR &UV/H ₂ O ₂		5	0.2-1.1	3.8days	COD removal- 97.7%		40
ABR		Inclined tube settler		12 hrs	COD removal- 95%	0.35m ³ CH ₄ /kgCOD	41
Modified ABR		9		6hrs	COD removal- 84%	0.34m ³ CH ₄ /kgCOD	42
Submerged membrane bioreactor		8		10hrs	COD removal>90%	60% methane gas	43

3.10. Sequencing batch reactor(SBR):

Sequencing batch reactor works in sequence in various cycles. It is a unique treatment process, with sequence of operation of filling, reaction, settling and effluent decanting occurring in one tank. SBR can be modified for removal of carbon and nitrogen separately.

Hydrogen production is also studied in SBR. Table-3 represents various types of SBR [44-48].

Table-3: Type of sequencing batch reactors

Type of SBR	Cycle period	OLR(kg COD/m ³)	Performance	Methane gas yield	Reference
Suspended growth SBR	24hrs(Fill-15min, React-23hrs, Settle-30min, Decant-15min)	3.5	H ₂ production-0.3683 mmol H ₂ /m ³ -min	-	44
AnSBR	3days	5.3	COD removal - 80%	-	45
Sequencing anoxic/anaerobic membrane bioreactor	Anoxic-3hrs Anaerobic-1hr	-	-		46
Internal circulation Anaerobic reactor with SBR(IC-SBR)	5-6days	6-7	COD removal-95.5%		47
An SBR		12.8	COD removal-80%	0.197dm ³ CH ₄ g ₁ COD	48

4. Factors effecting Anaerobic digestion:

Process of anaerobic digestion is affected by several factors in the reaction system. Process of anaerobic digestion includes variation of pH inside the reactor due to formation of volatile acids. It is governed by organic loading rate, hydraulic retention time, temperature and by nutrient availability inside the reactors.

4.1. Effect of pH:

Reactions in anaerobic reactors are highly pH-dependent. pH of 6.8-7.2 is more favourable for methanogens, whereas acidic pH is more favourable for acidogens. The pH of an anaerobic reactor is usually maintained between 6.8 and 7.2, to prevent the dominance of acid forming bacteria which could accumulate VFA. The effect of a pH-change in the wastewater inside the reactor depends on the available alkalinity in the reactor. Sodium bicarbonate is usually added to the reactors to neutralize any acids inside the reactors. Sodium bicarbonate does not disturb the physico-chemical balance of sensitive microbes [20] Methanogenesis is inhibited at pH exceeding 8, where sludge granules dominated by sulphate reducing bacteria, however process efficiency recovers once optimal pH is maintained[49,50].

4.2. Effect of temperature:

Temperature is an important influencing factor in anaerobic digestion process. Anaerobic digestion works in psychrophilic, mesophilic and thermophilic ranges. However, mesophilic ranges are found to be most suitable in most of the studies. Temperature is well resisted by microbes as long as they are not very high. Hydrolysis and acidogenesis is not effected by temperature, but methanogens are more sensitive towards temperature[20]. Methane production was found to remain high at 45 Deg C, however high temperatures resulted in drop in biogas production due to decay of bacteria [49]. A CSTR system was studied at different temperatures (50 & 60Deg C). The fluctuations were observed by decreasing and increasing the temperature by 10Deg C. Temperature variations were found to significantly affect the pH range and free ammonia concentrations, thereby affecting the hydrolysis, acidogenesis and methanogenesis steps [51]. Entrapment capacities of sludge bed, hydraulic shearing force of particles are affected by variations in temperature [52].

4.3. Effect of Nutrients:

Micro, Macro nutrients and trace elements like nitrogen, phosphorous, sulphur, potassium, calcium, magnesium, iron, nickel, cobalt, zinc, manganese and copper are essential for granulation process and maintaining stability of the reactors. These elements are required in very low concentrations, for bacterial growth and performance of the reactor. Methanogens have relatively high internal concentrations of iron, nickel and cobalt. Wastewater does not contain micronutrients in sufficient amounts thus supplements. The optimum C: N: P ratio was found to be 100:2.5:0.5 for enhanced yield of methane production [20]

4.4. Effect of organic loading rate & Hydraulic loading rate:

Loading rate plays a crucial role in anaerobic digestion process. A delicate balance exists between the primary processes like hydrolysis & acidogenesis and conversion of these products to methane and carbon dioxide. The fluctuations in hydraulic and organic loading rate are effected by hydraulic retention time (HRT), sludge retention time (SRT), reactor design, intensity and duration of variations. The accumulation of volatile fatty acids, thus decreasing the pH is a typical response when load

variations are observed [49]. Non-attached biomass reactors, where HRT are long, leads to biomass washout if loading rate goes high, leading to process failure, whereas for fixed film reactors can withstand high organic loading rate. Fixed film reactors, when compared to CSTRs have better stability, rapid restoration of systems are possible even in case of shock loads. Lower HRT and high organic loading rates also result in high treatment efficiency of COD [20].

5. Application of anaerobic reactors on High strength wastewaters:

5.1. Dairy wastewater:

The dairy industry wastewater generates strong characteristic wastewater high in biological oxygen demand (BOD) and chemical oxygen demand (COD). Dairy industry effluents flow rates are not constant. Seasonal variations are very frequent. Characteristics of dairy industry wastewater are given in Table-4 [53]. Table-5 represents type of reactors used for dairy wastewater and their performances. Upflow anaerobic sludge blanket (UASB) and sequential batch reactors (SBR) are studied for dairy wastewater with removal efficiencies more than 80%.

Table-4: Characteristics of dairy wastewater

Parameters	Concentrations(ppm)
pH	8-11
COD	6000-8000
BOD	1200-1400
Suspended solids	350-3000
Alkalinity	5-300

Table-5: Type of reactors for dairy wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Sequencing batch reactor (AnSBR)	COD-64.7%	2.4, 3.5, and 4.7 Kg COD/m ³ -day	24hrs	44
Sequencing batch reactor (AnSBR)	COD-68%	1.6-12.8 COD dm ⁻³ d ⁻¹	1day	55
Sequencing batch reactor (AnSBR)	COD-2500mg/l	0.5kg-cod/m ³ /d	1.5day	56
Upflow anaerobic sludge blanket (UASB)	COD -85% bod-90%	4 kgs cod/m ³ /d-1	20 hrs	53
Upflow anaerobic sludge blanket (UASB)	COD-90%		19hrs	8
Upflow anaerobic sludge blanket (UASB)	69% and 79% of COD & BOD	1.9 to 4.4 kgCOD/m ³ .d.	24 h	59

5.2. Distillery wastewater:

Distillery wastewater is the most polluting effluent among all the industries. Table-6 represents the characteristics of distillery wastewater. Organic content is very high to treat. Anaerobic digestion is successfully used for treatment of distillery wastewater because the BOD/COD ratio is around 2.50 which is desirable. UASB reactors, Anaerobic filter reactors, fixed bed reactors were studied for anaerobic digestion. COD removal efficiencies were above 80%. [57-60].

Table-6: Characteristics of distillery wastewater

Parameters	Concentrations(ppm)
pH	3-5.4
COD	65000-135000
BOD	30000-70000
Suspended solids	350
Total dissolved solids	80000

5.3. Brewery wastewater:

The brewery wastewater is released in huge volumes, with high organic content, throughout the year. The high organic loads in the wastewater arise from dissolved carbohydrates, alcohols from beer wastes, and a high content of suspended solids [11]. Table-7 represents, UASB, SBR and fluidized bed reactors are used for treatment of brewery wastewater. Pollutant removal was found to be above 85% in all the cases, with 8hrs- 24 hrs HRT, with OLR till 70kg COD/cu.m/d.

Table-7: Application of reactors for Brewery wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Upflow anaerobic sludge blanket (UASB)				61
Sequencing batch reactor	COD- >90%	1.5 kg COD/m ³ d and 5.0 kg COD/m ³ d	24 hrs	62
Upflow anaerobic sludge blanket (UASB)	85–90%, 4,000 mg l ⁻¹ COD	1 g COD l ⁻¹ day ⁻¹	24hrs	5
Upflow anaerobic sludge blanket (UASB)	COD-85%	11KG COD/m ³ /d-1	8hrs	63
Fluid Bed Reactor	COD-90%	70 kgCOD/m ³ d	1day	64

5.4. Domestic waste water:

Domestic wastewater or municipal wastewater is the most studied wastewater in anaerobic digestion process. Physico-chemical characteristics of a typical domestic wastewater are given in Table-8.[41]. Table-9 represents various technologies used for treatment of domestic wastewater. Hydraulic retention times of 2 hours to 6 hours have been studied.

Table-8: Characteristics of domestic wastewater

Parameters	Concentrations(ppm)
pH	7.5-8.2
COD	350-450
BOD	200-300
Suspended solids	300-450

Table-9: Application of reactors for domestic wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Anaerobic Baffle Reactor(ABR)	COD-86%, SS-81%		48hr	39
Anaerobic Baffle Reactor(ABR)	COD-85%, TSS-90%		48hr	38
Expanded granular sludge bed (EGSB) reactor	COD-90% and TOC-88%		3.5 to 5.7 h.	25
Fixed bed fixed film (FFFB)	90% and 95% of BOD and COD	0.0333 kg COD/m ³ /day	12 h	41
Fluid Bed Reactor	COD-90%	70 kgCOD/m ³ d	1day	64
Fed to Bench-Scale Anaerobic and Aerobic Bioreactors				65
Fluidized Bed Membrane Bioreactor	COD-99%	4.4-6.4 kg COD/m ³ /d	2.0-2.8h	66
Membrane bioreactor	COD-96.7%		8-12HRS	67
Fluidized-bed membrane bioreactor	COD-75.8%		8HRS	28
Submerged hollow-fibre membrane bioreactor	COD-90%		2hrs	29
Anaerobic membrane bioreactor	COD-2000–15,000 mg/L	4.5 kg/m ³ d	60Hrs	31
Anaerobic membrane bioreactors (AnMBR)	COD-85%	1 kg COD/m ³ d	12Hrs	32
Submerged anaerobic membrane bioreactor	COD-97%	1.10 to 1.65 kg COD m ³ d ⁻¹	8-12 hrs	33
Anaerobic membrane	COD-88%	1.08, 2.16 and 4.32	12, 6 and 4.5 h	68

bioreactor (AnMBR)		g COD/L/d		
Submerged anaerobic membrane bioreactor	COD-90%	~1.0kg COD/m ³ day	8–12 h	34
Membrane bioreactor			8-14HRS	69
Anaerobic submerged membrane bioreactor (AnSMBR)	COD-90%	0.6 to 1.1 g COD/L d	0.8 days.	70
Membrane bioreactor		100 kg [COD] m ³ d ⁻¹	1.6 to 48 hrs	71
Anaerobic membrane bioreactor (AnMBR)	COD->97%,BOD-91%	0.3 to 12.5 kg COD/m ³ day	10H-5.5H	72
Anaerobic membrane bioreactor (AnMBR)	COD-99%	0.02-2.36 kg m ³ d ⁻¹	2DAYS	73
Anaerobic membrane bioreactor (AnMBR)	COD-90%		3-48Hrs	74
Staged anaerobic fluidized membrane bioreactor (SAF-MBR)	COD-99%	1.0-1.2kg COD/m ³ -d	2.3H,3.4H	75
Moving bed biofilm reactor	COD-90-92%	4.1–15.7 kg COD m ³ d ⁻¹	14 hrs	76
Moving bed biofilm reactor	COD-94.4%	7–10 g BOD ₇ /m ² d	1 hrs	35
Sequencing anoxic/anaerobic membrane bioreactor (SAM)		4.0 kg COD/d	1-4hrs	46
Sequencing batch reactor			4 days	77
Anaerobic side-stream reactor	351 mg sCOD/L		1DAY	78
Completely mixed reactor & UASB	COD-98%	5.49 g COD dm ⁻³ d ⁻¹	12hrs	15
Upflow anaerobic sludge blanket (UASB)	65 - 80% for COD and BOD	4 g COD L ⁻¹ day ⁻¹	2-8hrs	79
Anaerobic Baffle Reactor(ABR)	SS-86% , BOD 87% and COD 84%	0.067 kgCOD/m ³ d	6hr	42
Mesophilic & Thermophilic anaerobic reactors	COD(meso)-21.26g/l COD(thermo)-22.36g/l		1day	80
Sequencing batch reactor (AnSBR)	cod-91%	2.6kg COD m ⁻³ d ⁻¹	4-24hrs	81

5.5. Textile wastewater :

Textile wastewaters are highly coloured effluents containing various dyes. The processes generating effluent in textile mills are desizing, scouring, bleaching, dyeing and printing. Major synthetic colorants contributing to textile effluents are Azo dyes. Studies reported that azo dyes can be degraded with anaerobic systems, as azo dyes are converted to aromatic amines. These aromatic amines inhibit further degradation [82]. UASB are most studied in textile wastewaters. COD removal efficiencies are above 85%. Table-10 represents various reactors applied for textile mill wastewater.

Table-10: Application of reactors in textile wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Semi-continuous bioreactors	COD-85-95%		96 hrs	83
Decolorisation Technique	> 60% COD			84
FFR,UASB,AFBR	60-80% COD	1 mg dm ⁻³	1-8HRS	85
Electro chemical anerobic reactor	COD-83.4%		24HRS	86

Upflow anaerobic sludge blanket (UASB)	COD-80%	1.0 to 15.8 kgm ⁻³ per day	6-100hrs	87
Upflow anaerobic sludge blanket (UASB)	COD-90%		24hrs	88
Upflow anaerobic sludge blanket (UASB)	~3000 mg/L COD		1.8-24hrs	13

5.6. Slaughter house wastewater:

Slaughter house wastewater contains lipids, proteins, blood and other organic material. Processing meat for human consumption generates lots of waste which eventually becomes wastewater. pH of slaughter house wastewater was found to be 6.1-7.1 with BOD between 4500-12000mg/l. [1].Table-11 represents applications of various reactors.

Table-11: Application of reactors in Slaughter house wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Anaerobic Baffle Reactor(ABR)	TOC-89.9%, COD-97.7%, and BOD-96.6%,		3.8day	40
Fixed-film reactor	SCOD-45%,SBOD-50%	0.77 kg COD/m ³ day	0.94 and 3.8 d	89
Fixed bed fixed film (FFFB)	COD and BOD of 93.7 and 93.96%,	4.37 kgTCODm ⁻³ d ⁻¹	1.25 days	90
Static Granular Bed Reactor (SGBR)	COD-higher than 94%.	1.64 kg COD/m ³ day	between 48 h and 10 h	26
Upflow anaerobic sludge blanket (UASB)	BOD-98 %, COD-5800 mg/l-1	3 kgs bod5/m-3/d-1	4 hrs	91

5.7. Olive mill wastewater

Olive mill wastewater has a wide range of characteristics depending upon the type of mill and type of olive. It has a pH between 5.15-5.93. COD of the olive mill wastewater is 55000-108000 ppm. Table-12 represents type of reactors used for treating olive mill wastewater. COD removal efficiency was above 70% in all cases. Highest hydraulic retention time studied was 17.7 days.

Table-12: Application of reactors in olive mill wastewater

Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Continuous lab-scale methanogenic reactor	COD-88%,BOD-68%		3.5 -17.7days	92
Continuous stirred tank reactor	COD-88.4%,VS-90.9%	12.02 g CODL ⁻¹ d ⁻¹	24 hrs	93
Anaerobic sequencing batch reactor	80% COD	5.3 kg COD/m ³ /d	3 day	45
Upflow anaerobic sludge blanket (UASB)	COD-70-80%	1-10 kg COD m ⁻³ d ⁻¹	4hrs	94

5.8. Other industrial wastewater:

Various types of anaerobic reactors are applied on different industrial wastewaters. Table -13 represents various anaerobic reactors applied for various industrial wastewaters.

Table-13: Application of reactors in various industries

Type of Wastewater	Type of Reactors	Pollutant removal	Organic Loading Rate(OLR)	Hydraulic retention time(HRT)	References
Low strength soluble waste water	Anaerobic Baffle Reactor(ABR)	COD-more than 90%	1.5 to 1.2 kg COD/m ³ d)	8hr and 10hr	95
Soybean protein processing wastewater	Anaerobic Baffle Reactor(ABR)	COD-92-97%,	6.0 kgCOD/m ³ d	39.5h	37
Sewage sludge	Mesophilic & Thermophilic anaerobic reactors		meso-2d,thermo-1d		96

Municipal solid wastes	Mesophilic & Thermophilic anaerobic reactors		0.392-3.084 gVSSydm ³ per day		97
Synthetic wastewater	Thermophilic anaerobic reactors	COD-708 mg/l		1day	98
Glucose	CSTR & UASB REACTORS			2–12 hr	16
Wastewater containing soap powder	Anaerobic fluidized bed reactor (AFBR)	COD-70%		18hrs	99
Industrial wastewater	Submerged anaerobic membrane bioreactor		15 g COD/L day	1DAY	100
Coke plant wastewater	Anaerobic–anoxic–oxic membrane bioreactor	COD-89.8%	0.95 to 1.99 kg/(m ³ d	40hrs	76
Semi solid organic waste from ortho fruit market	Plug flow type bioreactor	COD-76%		1day	101
CHEMICAL waste water	Discontinuous/sequencing batch reactor		2,4,5.6 & 4.8 kgCOD/m ³ -day	24hrs	44
Swine & raw waste water	Sequencing batch reactor (AnSBR)	COD-80%	6-7 kg COD/m ³ /d	1DAY	47
Azo dyes waste water	Anaerobic & aerobic sequencing batch reactor	cod-86.4%		7.4-14.7 hrs	102
Land fill leachate wastewater	Sequencing batch reactor (AnSBR)	cod-2000 mg/l, 85%	1.1kg, p-1, d-1	0.2 h -9 hrs	103
Sulphate bearing waste water	Sequencing batch biofilm reactor (ASBBR)	cod-60%	4kg cod/m ³ /d	1 day	104
Chemical waste water	Anaerobic sequencing batch biofilm reactor	cod-5890 mg/l	6.3 kg cod/m ³ /d	1 day	105
Synthatic waste water	Upflow anaerobic sludge blanket (UASB)	COD- 92%		6.7 hrs	106
Rice mill waste water	Upflow anaerobic sludge blanket (UASB)	COD-87%			107
Influent waste water	Upflow anaerobic sludge blanket (UASB)	BOD-300mg/l		1day	108
Pharmaceutical waste water	Upflow anaerobic stage blanket (UASB)	COD-70-75%	0.43-1.86 kgs cod/m-3/ d-1	4 days	109
Pulp And paper mill waste water	Upflow anaerobic sludge blanket (UASB)	COD-85 %	5.75 kg cod/m-3/d-1	20 hrs	110
Cheese-whey wastewaters	Upflow anaerobic sludge blanket (UASB)	COD-90%	28.5 and 9.5 g COD/l/day	1day	111
Organic waste and wastewater	Upflow anaerobic sludge blanket (UASB)				112

6. Conclusions:

Detailed review has been conducted on status of anaerobic digestion in waste water treatment from the year 2000. Types of reactors studied in this period have been critically explained. There are various types of reactors like SBR, AFBR, UASB, CSTR etc. Factors affecting the anaerobic digestion process were discussed. pH and organic loading rate was found to be the most important factors for anaerobic digestion process. Anaerobic reactors have been applied for various kinds of domestic and industrial wastewaters. Treatment efficiency was found to be above 70% in all the wastewaters. It can be concluded that anaerobic digestion process has been a robust technology for application in wastewaters for removal of organics.

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