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Review

A review on anaerobic–aerobic treatment of industrial and municipal wastewater

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ABSTRACT

Anaerobic–aerobic systems have been remarkably employed in industrial and municipal wastewater treatment for many years. While previously most treatment of wastewaters have been carried out in conventional anaerobic–aerobic treatment plants, in recent years, high rate anaerobic–aerobic bioreactors have been increasingly employed for wastewaters with high chemical oxygen demand (COD). This paper provides a review of the various types of high rate anaerobic–aerobic water treatment techniques currently available including high rate bioreactors and integrated anaerobic–aerobic bioreactors. The integrated bioreactors are classified into four types, which are (i) integrated bioreactors with physical separation of anaerobic–aerobic zone, (ii) integrated bioreactors without physical separation of anaerobic–aerobic zone, (iii) anaerobic–aerobic Sequencing Batch Reactors (SBR), and (iv) combined anaerobic–aerobic culture system. The integration of aerobic and anaerobic degradation pathways in a single bioreactor is capable of enhancing the overall degradation efficiency. The merits of different integrated anaerobic–aerobic bioreactors are highlighted and comparison made to identify possible future areas of research to fully utilize these methods of wastewater treatment. The comparison demonstrates that using an integrated bioreactor with stacked configuration in treating high strength industrial wastewaters is advantageous due to minimal space requirements, low capital cost and excellent COD removal efficiencies (in excess of 83%).

1. Introduction

Over the last century, continued population growth and industrialization have resulted in the degradation of various ecosystems on which human life relies on. In the case of ocean and river quality, such pollution is primarily caused by the discharge of inadequately treated industrial and municipal wastewater. On initial discharge, these wastewaters can contain high levels of inorganic pollutants which can be easily biodegradable, but whose impact load on the ecosystems, either in Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD_5), or Chemical Oxygen Demand (COD), may be in the tens of thousands mg/L [1]. To combat this increasing burden on our aquatic environment, increasingly strict regulation on pollution discharge is being implemented by various governmental bodies, with focus primarily on waste reduction. The treatment systems developed by industry are frequently regarded as a regulatory obligation, increasing capital and running costs and yielding negative economic returns. Compliance to environmental legislations should not necessary lead to the creation of additional costs, but can instead provide a secondary source of income. One possible source of increased revenue available to industries is through taking advantage of the incentives awarded by the Clean Development Mechanism (CDM) under the Kyoto Protocol 1997.

In the treatment of wastewater, biological treatment appears to be a promising technology to attain revenue from Certified Emission Reduction (CER) credits, more commonly known as carbon credits from the CDM as methane gas is generated from anaerobic digestion and can be utilized as renewable energy. With appropriate analysis and environmental control, almost all wastewaters containing biodegradable constituents with a BOD/COD ratio of 0.5 or greater can be treated easily by biological means [2]. In comparison to other methods of wastewater treatment, it also has the advantages of lower treatment costs with no secondary pollution [3]. Both aerobic and anaerobic processes can be used; the former involves the use of free or dissolved oxygen by microorganisms (aerobes) in the conversion of organic wastes to biomass and CO_2 while in the latter complex organic wastes are degraded into methane, CO_2 and H_2O through three basic steps (hydrolysis, acidogenesis including acetogenesis and methanogenesis) in the absence of oxygen. Aerobic biological processes are commonly used in the treatment of organic wastewaters for achieving high degree of treatment efficiency, while in anaerobic treatment, considerable progress has been achieved in anaerobic biotechnology for waste treatment based on the concept of resource recovery and utilization while still achieving the objective of pollution control [4,5].

The various merits of both treatments are highlighted in Table 1, and both systems are capable of achieving high organic removal

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Table 1
Comparison of aerobic and anaerobic treatment [4,7].

Feature	Aerobic	Anaerobic
Organic removal efficiency	High	High
Effluent quality	Excellent	Moderate to poor
Organic loading rate	Moderate	High
Sludge production	High	Low
Nutrient requirement	High	Low
Alkalinity requirement	Low	High for certain industrial waste
Energy requirement	High	Low to moderate
Temperature sensitivity	Low	High
Start up time	2–4 weeks	2–4 months
Odor	Less opportunity for odors	Potential odor problems
Bioenergy and nutrient recovery	No	Yes
Mode of treatment	Total (depending on feedstock characteristics)	Essentially pretreatment

efficiency. In general, aerobic systems are suitable for the treatment of low strength wastewaters (biodegradable COD concentrations less than 1000 mg/L) while anaerobic systems are suitable for the treatment of high strength wastewaters (biodegradable COD concentrations over 4000 mg/L). According to Cakir and Stenstrom [6], there exist cross over points, ranging from 300 to 700 mg/L influent wastewater ultimate BOD (BOD_u), which are crucial for effective functioning of aerobic treatment systems. The advantages of anaerobic treatment outweigh the advantages of aerobic treatment when treating influents in higher concentrations than the cross over values, and generally anaerobic treatment requires less energy with potential bioenergy and nutrient recovery. However, compared to anaerobic systems, aerobic systems achieve higher removal of soluble biodegradable organic matter material and the produced biomass is generally well flocculated, resulting in lower effluent suspended solids concentration [7]. As a result, the effluent quality from an aerobic system is generally higher than the anaerobic system.

Highly polluting industrial wastewaters are preferably treated in an anaerobic reactor due to the high level of COD, potential for energy generation and low surplus sludge production. However in practical applications, anaerobic treatment suffers from the low growth rate of the microorganisms, a low settling rate, process instabilities and the need for post treatment of the noxious anaerobic effluent which often contains ammonium ion (NH_4^+) and hydrogen sulfide (HS^-) [8]. In most applications, despite the efficiency of the anaerobic process is high, complete stabilization of the organic matter is impossible anaerobically due to the high organic strength of the wastewater. The final effluent produced by the anaerobic treatment contains solubilized organic matter. This is suitable for aerobic treatment, indicating the potential of using anaerobic–aerobic systems [9] and subsequent post treatment using aerobic treatment is required to meet the effluent discharge standard.

For green olive debittering wastewater with a COD varying between 25,000 and 100,000 mg/L, Aggelis et al. [10] found that neither anaerobic nor aerobic processes could be employed alone for efficient treatment. When treating these high organic strength industrial wastewaters, aerobic or anaerobic treatment alone do not produce effluents that comply with effluent discharge limit. The use of anaerobic–aerobic processes can also lead to a factor eight cost reduction in operating costs when compared with aerobic treatment alone [11], while simultaneously resulting in high organic matter removal efficiency, a smaller amount of aerobic sludge and no pH correction. Benefits of the anaerobic–aerobic process have been identified by Frostell [12] and Cervantes et al. [13] are listed below:

- Great potential of resource recovery: Anaerobic pretreatment removes most of the organic pollutants and converts them into a useful fuel, biogas.
- High overall treatment efficiency: Aerobic post-treatment polishes the anaerobic effluent and results in very high overall treatment efficiency. The aerobic treatment also smoothes out fluctuations in the quality of the anaerobic effluent.
- Less disposal of sludge: By digesting excess aerobic sludge in the anaerobic tank, a minimum stabilized total sludge is produced which leads to a reduction in sludge disposal cost. As an additional benefit, a higher gas yield is achieved.
- Low energy consumption: anaerobic pretreatment acts as an influent equalization tank, reducing diurnal variations of the oxygen demand and resulting in a further reduction of the required maximum aeration capacity.
- When volatile organics are present in the wastewater, the volatile compound is degraded in the anaerobic treatment, removing the possibility of volatilization in the aerobic treatment.

Thus it can be seen that it is operationally and economically advantageous to adopt anaerobic–aerobic processes in the treatment of high strength industrial wastewaters since it couples the benefit of anaerobic digestion (i.e. biogas production) with the benefits of aerobic digestion (i.e. better COD and volatile suspended solid (VSS) removal) [14]. As well as their capability to biodegrade organic matter, anaerobic–aerobic systems have also been found to perform well for the following processes: biodegradation of chlorinated aromatic hydrocarbons including anaerobic dechlorinations and aerobic ring cleavage [15]; sequential nitrogen removal including aerobic nitrification and anaerobic denitrification [16]; anaerobic reduction of Fe(III) and microacrophilic oxidation of Fe(II) with production of fine particles of iron hydroxide for adsorption of organic acids, phenols ammonium, cyanide, radionuclides, and heavy metals [17].

These advantages have prompted the rapid development of anaerobic–aerobic systems in the treatment of both industrial wastewater [18–22] and municipal wastewater (primarily designed for nutrient removal) [23–25]. While most treatment of industrial and municipal wastewaters has been carried out in conventional anaerobic–aerobic treatment plants, high rate bioreactors have been developed to reduce the capital cost of the process. However, the investigation on the high rate anaerobic–aerobic treatment are limited to a few studies and not well documented. Hence, this review aims to summarize and discuss the feasibility of high rate anaerobic–aerobic treatment for efficient organic removal of industrial and municipal wastewater. This review also provides an overview of different types of anaerobic–aerobic treatment system, providing a comparison between the conventional and newer technologies.

2. Types of anaerobic–aerobic treatment systems

Fig. 1 highlights the three main types of anaerobic–aerobic system currently in use, with distinctions made between the dif-

Table 2
Anaerobic–aerobic systems using high rate bioreactors.

No	Type[a]	Type of wastewater[b]	Influent COD (mg/L)	OLR[c] (kg COD/m^3 d)	Total COD removal (%)	Anaerobic COD removal (%)	Aerobic COD removal (%)	Total HRT[d] (h or d)	Anaerobic HRT[d] (h or d)	HRT[d] (h or d)	Reference
1	UASB + CSTR	Wool acid dying ww	499–2000	–	83–97	51–84	–	3.3 d	17 h	–	[26]
2	UASB + CSTR	Cotton textile mill ww	604–1038	–	40–85	9–51	–	5.75 d	30 h	4.5 d	[27]
3	UASB + CSTR	Simulated textile ww	4214	1.01–15.84	91–97	–	–	19.17–1.22 d	–	–	[28]
4	2 UASBs + CSTR	Food solid waste leachate	5400–20000	4.3–16	96–98	58–79	85–89	5.75 d	1.25 d	4.5 d	[20]
5	UASB + CSTR	Pulp and paper industry effluent	5500–6600	16	91	85	–	11.54 h	5 h	6.54 h	[29]
6	UASB + CSTR	Pharmaceutical industry ww	3000	3.6	97	68–89	71–85	–	–	–	[30]
7	UASB + AS	Olive mill ww + municipal ww	1800–4400	3–7	95–96	70–90	>60	28.3 h	14.7 h	13.6 h	[31]
8	UASB + AS	Starch Industry ww	20000	15	–	77–93	64	5 d	1 d	4 d	[32]
9	UASB + AS	Municipal ww	386–958	–	85–93	69–84	43–56	6.8 h	4 h	2.8 h	[33]
10	UASB + AFB	Synthetic textile ww	2000–3000	–	–	–	–	2.7–32.7 h	1.4–20 h	1.3–12.7 h	[34]
11	UASB + AFB	Synthetic textile ww	2700	4.8	80	50	60	20 h	10 h	10 h	[35]
12	RBC + SBR	Mixture of cheese whey and dairy manure	37400–65700	5.2–14.1	99	46.3–62.6	93–95	–	2–5 d	–	[21]
13	RBC + SBR	Screened dairy manure	39900–40100	8.2–26.8	98	18.7–29	86–87	–	1–4 d	–	[36]
14	FFB + FFB	Slaughter house ww	400–1600	0.39	92	–	–	4.7–7.3 d	1.2 d	3.5–6.1 d	[37]
15	EGSB + Aerobic biofilm reactor	POME	35000	10	95.6	93	22	–	3 d	–	[22]
16	UBF + MBR	Synthetic ww	6000–14500	7.2	99	98	–	1 d	–	–	[18]
17	UASB + Aerobic solid contact system	Municipal ww	341	2.6	–	34	–	3.53–6.2 h	3.2 h	0.33–3 h	[23]
18	UASB + RBC	Domestic sewage	640	–	84–95	35–47	52–56	6–13.5 h	3–6 h	3–7.5 h	[24]
19	CSTR + Activated sludge	Green olive debittering ww	23500	0.47	83.5	37.4– 48.9	73.6	55 d	50 d	5 d	[10]
20	AFFFBR + AS	PTA effluent	5000	4–5.0	96.4	64–62	90	23–27.2 h	1–1.2 h	22–26 h	[38]
21	AnFB + Air lift suspension reactor	Complex industrial ww	3800	25–30	–	60–65	–	3.4–4.3 h	1.4–1.8 h	2–2.5 h	[8]

Table 2 (*Continued*)

No	Type[a]	Type of wastewater[b]	Influent COD (mg/L)	OLR[c] (kg COD/m^3 d)	Total COD removal (%)	Anaerobic COD removal (%)	Aerobic COD removal (%)	Total HRT[d] (h or d)	Anaerobic HRT[d] (h or d)	HRT[d] (h or d)	Reference
22	Hybrid bioreactor + AS	Oil shale ash dump leachate	2000–4600	–	75	20–40	60–80	8.8 d	62 h	150 h	[39]
23	Packed column reactor + AS	Textile industry ww	800–1200	–	50–85	30–65	40–90	22–82 h	12–72 h	10 h	[40]

[a] Reactor Type: UASB, upflow anaerobic sludge bed; CSTR, continuously stirred tank reactor; AS, activated sludge; AFB, aerobic fluidized bed; RBC, rotating biological contactors; SBR, sequencing batch reactor; FFB, fixed film bioreactor; EGSB, expanded granular sludge bed; UBF, upflow bed filter; AFFFBR, anaerobic fixed film fixed bed reactor; AnFB, anaerobic fluidized bed.

[b] Type of waste water (ww): POME, palm oil mill effluent; PTA, purified terephthalic acid.

[c] OLR, Organic loading rate.

[d] HRT, Hydraulic retention time: h, hour; d, day.

ferent approaches used to obtain an anaerobic–aerobic reactor system.

The simplest approach for the anaerobic–aerobic treatment is the use of conventional systems such as aerated stabilization ponds, aerated and non-aerated lagoons, as well as natural and artificial wetland systems. Aerobic treatment occurs in the upper part of these systems while anaerobic treatment occurs at the bottom end. A typical organic loading is 0.01 kg BOD/m^3 day and the retention time varies from a few days to 100 days [17].

Conventional anaerobic–aerobic systems usually comprise large ponds connected in series and are frequently characterized by long hydraulic retention time (HRT), low organic loading rate (OLR), as well as vast area of land or digesters. In short, the conventional treatment plants suffer from problems related to their large space requirement, emissions into populated environments from large open reactors, low process efficiencies, large surplus sludge production and high energy consumption. These eventually decrease the attractiveness of conventional anaerobic–aerobic treatment plants for reasons of economy and location.

New technologies have been developed over the years to overcome the disadvantages of conventional anaerobic–aerobic systems. Anaerobic–aerobic system using high rate bioreactors (such as upflow anaerobic sludge blanket (UASB), filter bioreactor, fluidized bed reactor, membrane bioreactor) are adopted in order to provide a treatment process which is both technologically and economically viable with the dual goals of resource recovery and compliance with current legislation for effluent discharge. A more intensive form of biodegradation can also be achieved by integrating anaerobic and aerobic zones within a single bioreactor. Essentially, there are four types of integrated anaerobic–aerobic bioreactor. These are (i) integrated bioreactors with physical separation of anaerobic–aerobic zone, (ii) integrated bioreactor s without physical separation of anaerobic–aerobic zone, (iii) Sequencing Batch Reactors (SBR) based on temporal separation of the anaerobic and the aerobic phase, and (iv) combined anaerobic–aerobic culture system based on the principle of limited oxygen diffusion in microbial biofilms. An overview of the most frequently applied bioreactors is delineated in Tables 2–4, with specific attention on the evaluation of their treatment efficiency in terms of organic removal.

3. Anaerobic–aerobic systems using high rate bioreactors

The right combination and sequence of treatment methods is the key to the successful handling of industrial and municipal wastewater. The combinations of different anaerobic and aerobic bioreactors have been applied to treat a broad range of industrial wastewater including textile industry wastewater, food solid waste leachate, pulp and paper industry wastewater, pharmaceutical industry wastewater, mixture of olive oil mill wastewater and primary municipal wastewater, starch industry wastewater, green olive debittering wastewater, slaughter house wastewater, and palm oil mill effluent (POME). Table 2 lists the anaerobic–aerobic systems using high rate bioreactors where the treatment is carried out in two separate bioreactors connected in series. The anaerobic–aerobic systems using high rate bioreactors reviewed in this paper achieve high COD removal (in excess of 70%) at short HRT (ranging from few hours to few days). Therefore, the anaerobic–aerobic treatment is an efficient method to treat industrial and municipal wastewater.

3.1. Upflow Anaerobic Sludge Bed (UASB) and Continuous Stirred Tank Reactor (CSTR) system

Upflow Anaerobic Sludge Bed (UASB) reactors appear to be a robust technology and have performed well in wastewater treat-

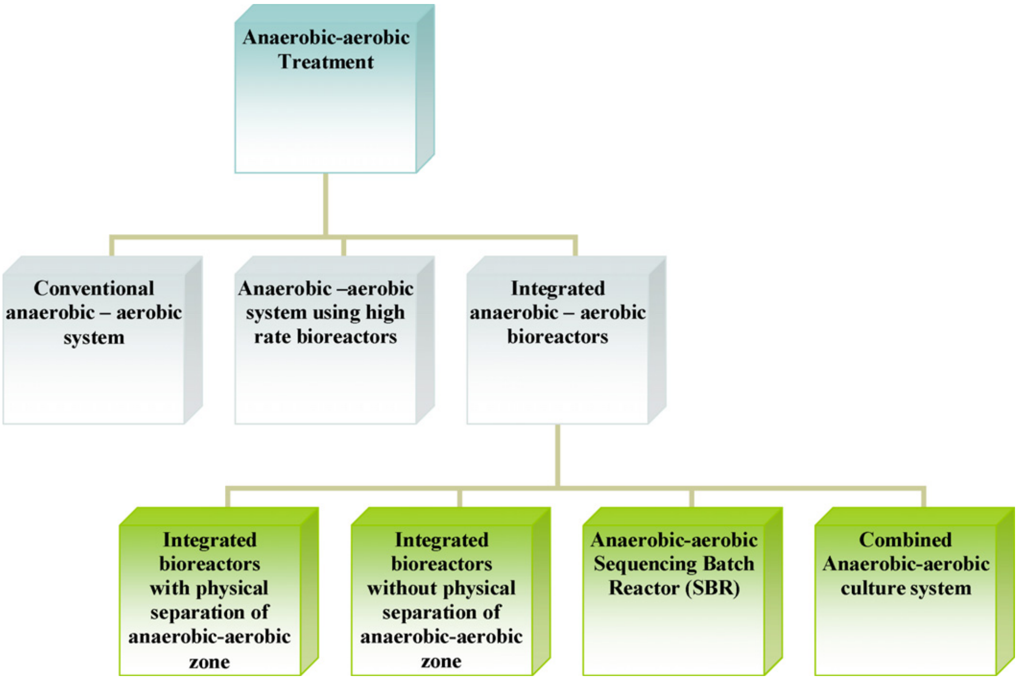

Fig. 1. Types of combined anaerobic–aerobic system.

ment for a number of decades [5]. They are extensively exploited as a pre-treatment before aerobic treatment for various types of industrial and municipal wastewaters. It has shown to be a technology proficient in overcoming some of the disadvantages of the mechanized aerobic systems, due to the lower energy consumption and sludge generation. A schematic of an UASB system is shown in Fig. 2. It consists of an upflow of wastewater through a dense sludge bed with high microbial activity [41,42]. The processes are based on the development of dense granules (with diameter of 1–4 mm) formed by the natural self-immobilization of the anaerobic bacteria, considered to be an essential condition for the successful operation of a UASB reactor. Suspended and colloidal components of wastewaters in the form of fat, protein, and cellulose have adverse impact on the performances of UASB reactors, preventing the system from operating at high organic loading rates and can cause deterioration of microbial activities and wash out of active biomass [43]. Generally, UASB are reported to remove more than 60% of COD from most types of wastewater. Impressive though this is, UASB treated effluent usually fails to comply with most of discharge standards [33].

Activated sludge, which consists of stirred and aerated flocculated suspension of a mixed bacterial population that comes into contact with wastewater, is the most commonly used process in aerobic treatment [44]. It has high efficiency with operational flexibility and possibility for nutrient removal. The activated sludge process can be a plug flow reactor (PFR), continuously stirred tank reactor (CSTR), or sequencing batch reactor (SBR). However, operating activated sludge system alone requires a high level of mechanization, high construction and operational costs, sophisticated operation and the need for treating a substantial amount of sludge.

Balancing the advantages and disadvantages of both systems, a combined technology, consisting of an UASB reactor for anaerobic pretreatment, followed by activated sludge for aerobic post treatment has been extensively employed [32,33]. A significant feature of this system is the return of the excess aerobic sludge to the UASB reactor where the solids undergo stabilization, and thus simplify the sludge treatment. The overall sludge production of the anaerobic–aerobic system is wasted only from the UASB reactor. Since it is already thickened and stabilized, it can be directly sent for dewatering and final disposal.

Several authors have validated the utility of UASB/aerobic CSTR system for tackling a wide variety of industrial wastewaters with BOD/COD ratio ranging from 0.17–0.74 [20,26–33]. Based on the data shown in Table 2, the UASB/aerobic CSTR systems can typically remove 83–98% of COD with influent COD content in the range of 500–20,000 mg/L at a total HRT of 11.54 h to 6 days.

Table 3
Integrated bioreactors with physical separation of anaerobic and aerobic zones.

No	Bioreactor Type[a]	Type of Wastewater[b]	Influent COD (mg/L)	OLR[c] (kg COD/m^3 d)	Total COD removal (%)	Anaerobic COD removal (%)	Aerobic COD removal (%)	Total HRT[d] (h)	Reference
1	Bubble column with a draught tube	Synthetic ww	–	–	–	–	–	3–11	[69]
2	RAAIB bioreactor	Sewage	345	–	84	–	–	1.2–15.5	[68]
3	SAA bioreactor	Diluted landfill leachate	1000–3300	–	85–95	–	–	–	[70]
4	Anaerobic aerobic integrative baffled reactor	Potato starch ww	1100–4500	–	88.4–98.7	87	–	6–24.0	[67]

[a] Bioreactor Type: RAAIB, Radial anaerobic/aerobic immobilized biomass; SAA, Simultaneous aerobic and anaerobic bioreactor.

[b] Type of wastewater (ww).

[c] OLR, Organic loading rate.

[d] HRT, Hydraulic retention time: h, hour.

Table 4
Integrated bioreactors without physical separation of anaerobic and aerobic zones.

No.	Type	Type of Wastewater[a]	Influent COD (mg/L)	OLR[b] (kg COD/m^3 d)	Total COD removal (%)	Anaerobic COD removal (%)	Aerobic COD removal (%)	Total HRT[c] (h or d)	Reference
1	Upflow anaerobic/aerobic fixed bed integrated reactor	Synthetic ww	365–3500	0.8–7.6	95–98	27–70	37–92	9 h	[84]
2	Anaerobic–aerobic granular biofilm reactor	Degradation of Aroclor 1242	–	–	–	–	–	2.1 d	[82]
3	Anaerobic–aerobic granular biofilm reactor	Degradation of TCE	800	–	–	–	–	17–20 h	[66]
4	Methanogenic–methanotrophic hybrid reactor	Degradation of PCE & TCE	–	–	–	–	–	0.5–3 d	[78]
5	Anaerobic–aerobic granular biofilm reactor	Synthetic ww	–	2.89–3.75	95–98	62–95	0–33	48 h	[79]
6	Staged anaerobic–aerobic membrane bioreactor	Synthetic ww	1300–10500	10.08	>99	60–80	–	–	[83]
7	Integrated anaerobic–aerobic fixed film reactor	Slaughterhouse ww	1190–2800	0.77	93	0.6–1.2	97	0.94–3.8 d	[81]
8	Integrated anaerobic–aerobic fluidized bed reactor	Municipal ww	350	<1.2	>80	–	–	24 h	[80]

[a] Type of wastewater (ww): TCE, Trichloroethylene; PCE, tetrachloroethelene.
[b] OLR, Organic loading rate.
[c] HRT, Hydraulic retention time: h, hour; d, day.

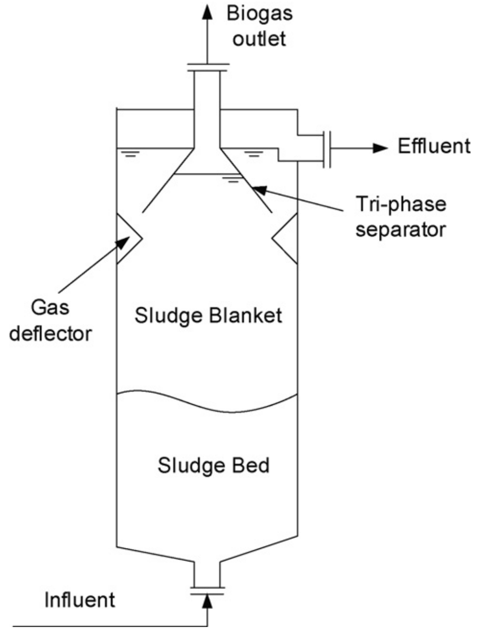

Fig. 2. Schematic representation of an UASB reactor [41]. (Reprinted from Biological Wastewater Treatment in Warm Climate Regions, p. 723, ISBN 9781843390022 with permission from the copyright holders, IWA).

Lerner et al. [45] presented a comparison between the results of paper mill wastewater treatment of a full-scale activated sludge treatment system working as the only biotreatment and the activated sludge treatment with anaerobic pretreatment by UASB. The anaerobic–aerobic system manifests steady operation performance, while the activated sludge treatment system without anaerobic pretreatment produced effluent with oscillatory quality. The results indicate a higher level of organic matter removal in the anaerobic–aerobic treatment system, with a final discharge of 80–120 mg COD/L as compared to 220–250 mg COD/L for the activated sludge treated effluent. It also illustrated that the anaerobic–aerobic treatment greatly reduced electrical consumption in the biological treatment plant and thus lowers operational costs.

3.2. UASB and aerobic fluidized bed (AFB) system

Fluidized bed reactors are packed with mobile supports in which particles covered with biofilm are fluidized by the recirculation of liquid. They eliminate substrate diffusion limitations, which are usually inherent in stationary bed process. A schematic of an aerobic fluidized bed (AFB) system is illustrated in Fig. 3. The AFB reactor exhibits numerous advantages such as a high biomass concentration, high OLR, short HRT, no bed clogging, small external mass transfer resistance and large surface area for mass transfer [46–48]. Conversely, there are some problems which inhibit their applicability on a large industrial scale such as control of the bed expansion, thickness of the biofilm and oxygen distribution system as well as high-energy consumption due to the very high liquid recirculation ratio [49,50]. The most common operational mode of an AFB reactor in wastewater treatment contains three phases: (i) the discrete solid phase of inert particles with immobilized microbial cells, (ii) the discrete air bubbles and (iii) the continuous aqueous solution.

Tavares et al. [51] showed that a high average COD removal efficiency (82%) was obtained in the treatment of a synthetic wastewater with feed COD content of 180 mg/L when the three-phase AFB is operated at a low average HRT (30 min). This result indicates the potential of this reactor to treat low strength wastewaters with COD content in the range of 100–200 mg/L.

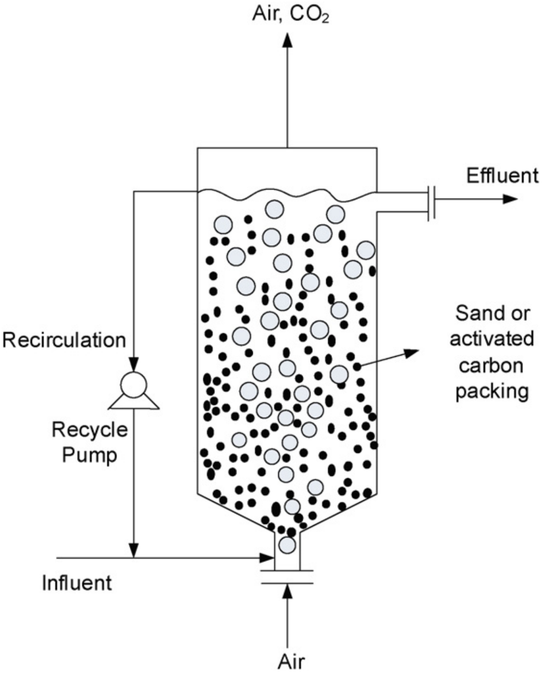

Fig. 3. Schematic representation of an AFB reactor [41]. (Modified from Biological Wastewater Treatment in Warm Climate Regions, p. 717, ISBN 9781843390022 with permission from the copyright holders, IWA).

By incorporating an UASB with the AFB reactor, a total COD removal efficiency of 75% at an overall HRT of 14 h can be accomplished in the treatment of a medium strength synthetic textile wastewater with 2700 mg COD/L [35]. The results revealed that the combined UASB–AFB system produced 45% lower sludge volume than the aerobic system.

However, Yu et al. [35] pointed out that the anaerobic biomass (∼1 g volatile solid (VS)/L) brought into AFB reactor contributed to an increase in suspended solids, rather than improved COD removal, because of its fast deactivation under aerobic conditions. The dead anaerobic cells diluted the specific activity of aerobes. Thus, the cell mass brought from the UASB reactor to the AFB reactor should be minimized to avoid a high turbidity with nil contribution in biological activity by the anaerobes.

The UASB-AFB system is useful in the biological treatment of medium strength industrial wastewaters due to its high pH tolerance, reduced sludge formation and stable COD removal performance. The UASB-AFB configuration emerges as an attractive alternative from technical, economical and environmental points of view, especially when space is a limiting factor.

3.3. *Anaerobic rotating biological contactors (RBC) and aerobic sequencing batch reactor (SBR) system*

In a rotating biological contactor (RBC) system, microorganisms attach to an inert support medium and form a biological film. The support medium, with a sequential disc configuration, is partly or totally submerged and rotates slowly around a horizontal axis in a tank through which the wastewater flows. A schematic of an RBC reactor is shown in Fig. 4. The system configuration of anaerobic RBC is similar to that of the aerobic RBC, except that the tank is covered to avoid contact with air [41]. When employing anaerobic RBC alone for treating high-strength synthetic wastewater with COD concentrations between 3248 and 12150 mg/L, the final COD of the RBC effluent is still considered too high. Thus, a further treatment is required albeit satisfactory efficiencies of overall COD removal ranged from 74 to 82% are achieved at a HRT of 32 h [52].

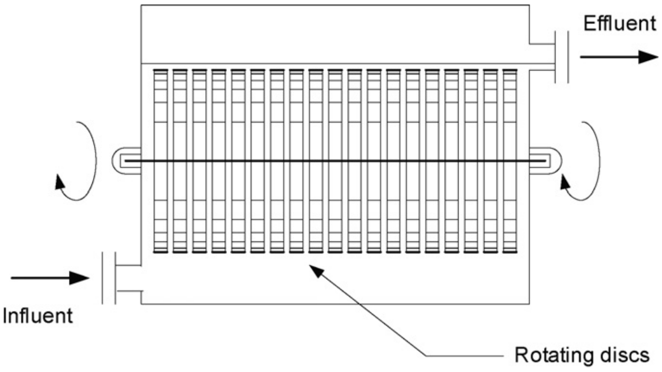

Fig. 4. Schematic representation of an anaerobic RBC reactor [41]. (Reprinted from Biological Wastewater Treatment in Warm Climate Regions, p. 719, ISBN 9781843390022 with permission from the copyright holders, IWA).

Advantages of the RBC system are low energy requirements, short retention time, excellent process control, low operating costs and that it is capable of handling a wide range of flows. Disadvantages include its process performance being susceptible to wastewater characteristics, resulting in limited operational flexibility to varying loading and operating conditions [7] and frequent maintenance on its shaft bearings and mechanical drive units.

The aerobic sequencing batch reactor (SBR) is an improved version of the fill and draw activated sludge system, consisting of one or more tanks, each capable of waste stabilization and solids separation [2]. The SBR process offers flexibility in the treatment of variable flows, minimum operator interaction, option for aerobic or anaerobic conditions in the same tank, good oxygen contact with microorganisms and substrate, small floor space, and good removal efficiency [53]. These advantages justify the recent increase in the implementation of this process in industrial [21,36,54] and municipal [55–57] wastewater treatment.

Since the anaerobic RBC can attain high methane production rates and the aerobic SBR process can treat dilute wastes efficiently, combining the two processes result in an efficient bioenergy production and waste treatment system. Hence, an anaerobic RBC integrated with three aerobic SBRs has been adopted in the treatment of screened dairy manure and a mixture of cheese whey with dairy manure [21,36]. Generally, this combined system is able to achieve apparent COD reduction of at least 98% and also produces substantial amounts of methane gas.

3.4. *Anaerobic–aerobic fixed film bioreactor (FFB) system*

Immobilized cells on the surface (fixed-film) of the media offer some advantages over cultures in suspension such as; a greater variation in population; less sensitivity to environmental variations (temperature, pH, and toxic substances); higher growth rate; faster utilization of the substrate in relation to free biomass. This is attributed to physiological modification of the fixed cells undergo, due to either the increase in the local concentration of nutrients and enzymes, or the selective effect of the extracellular polymeric matrix in relation to inhibitory or toxic substances [58].

The combination of two fixed-film bioreactors (FFB) with arranged media, the first anaerobic and the second aerobic, connected in series with recirculation for treatment of poultry slaughterhouse wastewater was evaluated by Del Pozo and Diez [37]. Owing to the high oil and grease (O&G) content in slaughterhouse wastewater which will cause serious flotation problems in suspended biomass systems, FFB was chosen in this system. Long corrugated PVC tubes were placed vertically as support media to avoid clogging, while the rough structure of the tubes increased their specific surface and protected the attached biomass from

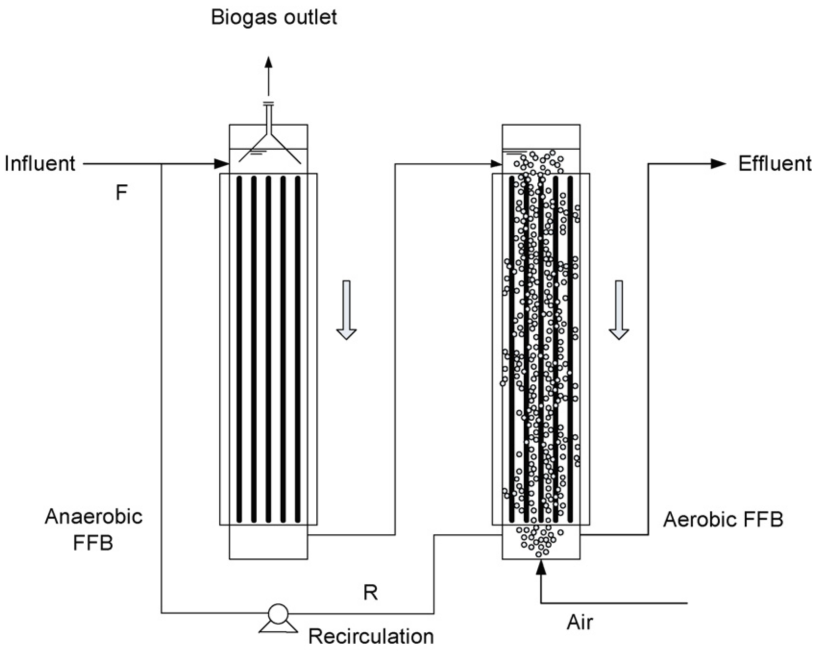

Fig. 5. Schematic diagram of anaerobic–aerobic FFBs [37]. (Reprinted from Water Research, Organic matter removal in combined anaerobic-aerobic fixed-film bioreactors, 37 (2003) 3561–3568, with permission from the copyright holders, Elsevier).

stress forces. Promising results were obtained, with an overall COD removal efficiency of 92% at OLR of 0.39 kg COD/m^3 day. A schematic of anaerobic–aerobic FFB is shown in Fig. 5.

Effects of recirculation ratio (R/F) and anaerobic/aerobic volume ratio (V_{an}:V_{ae}) on the fraction of COD removed by each reactor were evaluated. The FFBs were operated in a down flow manner and the aerobic effluent was recirculated to the anaerobic FFB. COD removal occurred mainly in the anaerobic FFB and this effect was accentuated when the recirculation ratio rose from 1 to 6 as a result of the increased contribution of denitrification. Besides, the fraction of COD removed in the anaerobic FFB increased when the volume of the aerobic FFB became smaller than anaerobic FFB. High recirculation in the anaerobic FFB feed favored the denitrification to the detriment of the methanogenic process and the production of biogas.

3.5. *Expanded granular sludge bed (EGSB) and aerobic biofilm reactor system*

The expanded granular sludge bed (EGSB) reactor comes under the family of UASB reactors. It has been primarily developed to improve the substrate–biomass contact within the treatment system by means of expanding the sludge bed with a high upflow liquid velocity (>4 m/h) which intensifies hydraulic mixing and results in better performance and stability than the UASB. The high upflow liquid velocity in the reactor is achieved through the application of a high effluent recirculation rate, coupled with a high height/diameter ratio of around 20 or more [41]. Fig. 6 depicts the schematic diagram of EGSB. They have been successfully applied to treat various kinds of wastewater including brewery wastewater, starch wastewater, molasses alcohol slops, slaughterhouse wastewater, POME, domestic and municipal wastewater [5,19]. However, EGSB is not suitable for the removal of particulate organic matter due to the high upflow liquid velocity. The influent suspended solids that are not retained by the granular bed will eventually leave the reactor together with the effluent [59].

Through utilizing an EGSB reactor, Zhang et al. [19] reported a high COD removal of 91% for a HRT of 48 h in the treatment of high organic strength wastewater with feed COD content of 80,000 mg/L. However, like other anaerobic systems, the EGSB is still unable to produce final effluent that complies with discharge standards.

In a recent study by Zhang et al. [22] for POME treatment, a total COD reduction of 95.6% at high OLR of 10 kg COD/(m^3 day) was achieved in a pilot-scale plant composed of an EGSB reactor and aerobic biofilm reactor. The anaerobic EGSB degraded a large portion of organic matter in POME with 93% COD removal while the aerobic biofilm reactor broke down the remaining organic

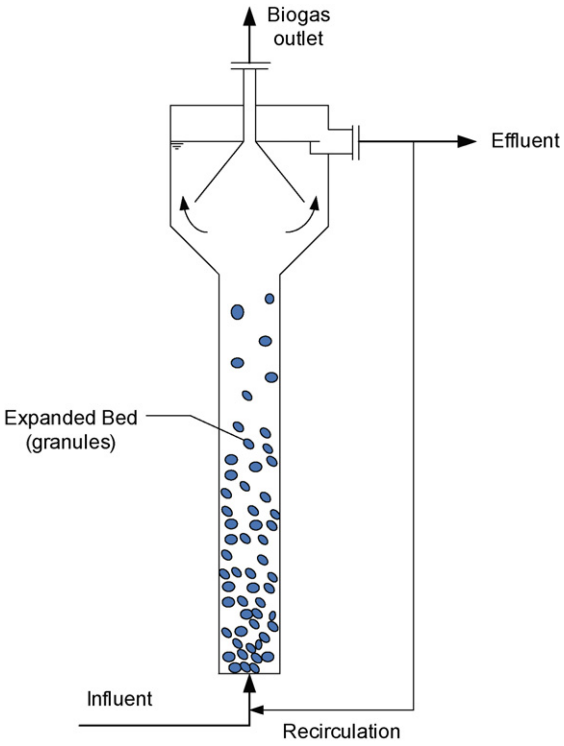

Fig. 6. Schematic diagram of EGSB [41]. (Reprinted from Biological Wastewater Treatment in Warm Climate Regions, page 724, ISBN 9781843390022 with permission from the copyright holders, IWA).

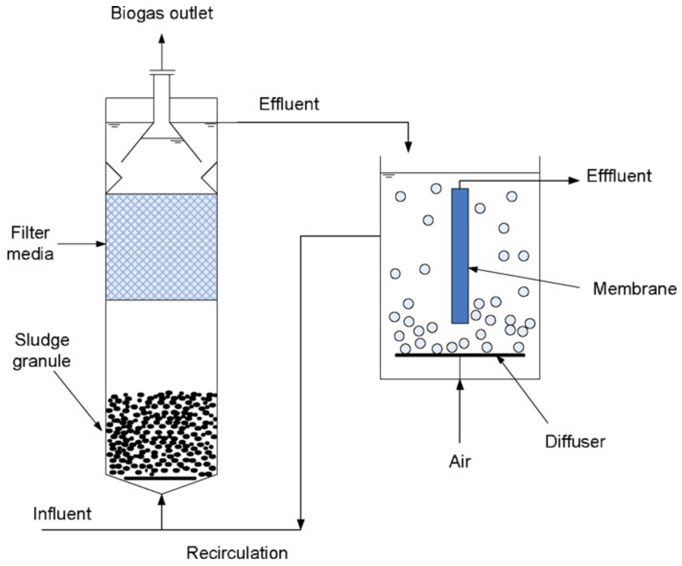

Fig. 7. Schematic diagram of UBF-aerobic MBR system [18]. (Reprinted from Desalination, Simultaneous high-strength organic and nitrogen removal with combined anaerobic upflow bed filter and aerobic membrane bioreactor, 202 (2007) 114–121, with permission from the copyright holders, Elsevier).

matter (22% of COD removal). In this case the reported average rate of organic matter transformed into methane in the EGSB was only 43% (based on the data of biogas measured), although this could be attributed to the high suspended solids and oil in POME.

3.6. *Anaerobic upflow bed filter (UBF) and aerobic membrane bioreactor (MBR) system*

Anaerobic upflow bed filter (UBF) is an anaerobic hybrid reactor which combines a UASB and anaerobic FFB. The lower part of the UBF reactor is the UASB, where granular sludge is developed. With the presence of stationary packing material, the upper part of the UBF serves as a FFB. The main advantage of the UBF is its ability to eliminate the problems of clogging and biomass washout which are commonly encountered in anaerobic FFB's and UASB's respectively.

Aerobic membrane bioreactors (MBR) combine membrane filtration with biodegradation processes, where solid–liquid separation occurs through sieving. In a MBR, solid materials, biomass, pathogenic bacteria, and even macromolecules are retained while allowing water and smaller solution species to pass through the membrane [60,61] so that a very high quality effluent is attained. MBRs offer numerous advantages which include the high quality of the effluent, the separation of solid retention time (SRT) from HRT, the reduced sludge production due to endogenous respiration in long SRT, and low sludge loading rate [62–64]. The membrane-retained aqueous and particulate based enzymes which are otherwise lost in the conventional sedimentation–clarification step are also able to improve the metabolic rate in the MBR [65]. While there are numerous advantages, one of the major obstacles in the application of MBR's is membrane fouling, with cross-flow filtration being most commonly used to alleviate this problem.

Ahn et al. [18] reported an apparent COD removal of 99% in the treatment of high-strength wastewater with COD content in the range of 6000–14,500 mg/L by the use of an anaerobic UBF-aerobic MBR system at a relatively short HRT of 24 h. A schematic diagram of the system is shown in Fig. 7. While this is impressive, it was noted that membrane fouling was observed and the transmembrane pressure (TMP) was about 9 times higher than that of a unit MBR operated under the same conditions. In this case the severe fouling in the system is caused by increased extracellular polymeric substance (EPS) and hydrophobicity.

3.7. *Process control and optimization for COD removal in anaerobic–aerobic systems using high rate bioreactors*

Optimization of the COD removal in anaerobic or aerobic bioreactors is more complex than in single stage as the performance of both stages is coupled. To obtain a large degree of depuration at the lowest capital and operational costs, the ideal size of each part of the anaerobic–aerobic system must be determined by an optimization of the anaerobic–aerobic treatment system. It is important to minimize the carbon removed by oxidation in order to reduce oxygen consumption, sludge production and the competition for oxygen between nitrifying and heterotrophic bacteria.

With increased removal of organic matter in the anaerobic reactor, the volume required for the aerobic reactor is reduced with a resulting drop in aeration cost. As aeration is one of the main individual operating costs, optimization of the conversion in the anaerobic reactor and minimization of the aerobic reactor size are exceptionally important. While the anaerobic reactor capital cost increases with increasing anaerobic yields, this increase is rather low compared to the total costs. Minimization of the aerobic reactor size can be carried out with adequate control of a sufficient amount of oxygen so as to maximize the conversion rates. It can be accomplished by utilizing oxygen instead of air which has been proved to reduce the treatment cost significantly [11].

However, if high extent of COD removal is accomplished in the anaerobic reactor, inadequate COD or other nutrients left in the effluent may not favor the performance of aerobes in the following aerobic reactor. Hence, in the optimization of the COD removal in the anaerobic reactor, it is crucial to ensure sufficient but not excessive COD left in the anaerobic bioreactor effluent for effective functioning of the aerobic bioreactor.

The minimization of anaerobic biomass brought into the aerobic reactor is crucial in the optimization of the anaerobic–aerobic system. As the aerobic reactor accepts an effluent directly from an active anaerobic digester, a significant amount of obligate anaerobes as well as facultative microorganisms enter the aerobic reactor and are not quickly adapted to the aerobic conditions. These active anaerobes could affect the cell population in the aerobic reactor and lead to a mixed microbial population of low oxygen utilization and biological activity. The anaerobic cells will not contribute to COD removal in the aerobic reactor, but increase the suspended solid concentration or the turbidity in the final effluent which puts an extra burden on the downstream sedimentation.

4. Integrated anaerobic–aerobic bioreactors

In recent years, substantial attention has been paid towards the compact high-rate bioreactors for wastewater treatment to meet the strict constraints with respect to space, odor, view, and biosolids production. Thus, the integrated bioreactors which combine the aerobic and anaerobic processes in a single reactor are seen as a viable alternative.

A combination of aerobic and anaerobic degradation pathways in a single reactor is capable of enhancing the overall degradation efficiency [66]. The integrated bioreactors are cost effective, efficient and have smaller foot prints as compared to the aforementioned anaerobic–aerobic systems. Nonetheless, the design, operation and process development of integrated anaerobic–aerobic bioreactors are still in its infancy and limited to a few studies.

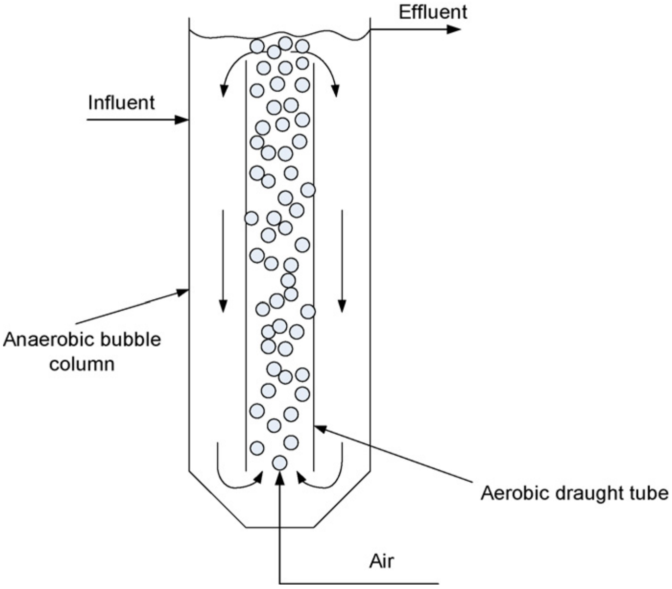

Fig. 8. Schematic diagram of the bubble column with a draught tube [69]. (Reprinted from Chemical Engineering Science, Biological nitrogen removal in a bubble column with a draught tube, 47 (1992) 3737–3744, with permission from the copyright holders, Elsevier).

4.1. Integrated bioreactors with physical separation of anaerobic and aerobic zones

Some approaches have been attempted to obtain the integrated bioreactors by combining anaerobic and aerobic processes in separate zones, such as the baffled reactors [67], the radial anaerobic/aerobic immobilized biomass (RAAIB) reactor [68] and employing an air-lift system for recirculation [69,70]. The data pertaining to the performance of those integrated bioreactors with physical separation of the anaerobic and aerobic zones are presented in Table 3.

4.1.1. Bubble column with a draught tube

A cylindrical bubble column with a draught tube as shown in Fig. 8 was employed as a small and simple treatment unit of anaerobic–aerobic activated sludge processes by Hano et al. [69] and more recently Bando et al. [71]. The performances of the unit proposed were evaluated based on the nitrogen removal.

The inside of a draught tube is used as an aerobic zone and the annulus as an anaerobic zone. The wastewater is initially introduced to the upper part of the annulus (anaerobic zone) and then flows with the sludge into a draught tube (aerobic zone) by the air-lift action. Finally the effluent is withdrawn from the top of the draught tube.

The volume ratio of anaerobic and aerobic zones in the bubble column can be adjusted simply by changing the diameter of the draught tube. The circulation flow rate of mixed liquor between the two zones is the most important parameter of operation in the anaerobic–aerobic activated sludge processes. It can be varied by changing the height of the draught tube and the flow rate of air into the draught tube. The increase in the circulation rate will cause aerobic conditions to prevail in the annulus which is meant to be anaerobic. As a result, the bubble-column treatment unit should be operated at the lowest circulation rate that can keep the sludge in suspending state.

The advantage associated with the bubble column is no requirement for additional equipment to circulate the mixed liquor between aerobic and anaerobic compartments. Hano et al. [69] demonstrated that the bubble column can be used as a small scale treatment unit, since a satisfactory performance is achieved with relatively simple apparatus and operation. However, the residence time in each zone during the circulation of liquid is too short compared to other anaerobic–aerobic activated sludge processes. Longer residence times are difficult to obtain as a minimum circulation flow rate is required to keep the sludge in a suspended state.

There are several studies which employed rectangular airlift bubble columns installed with support material for enhanced nitrogen removal [72–74]. The installation of the support material reduces the minimum circulation flow rate. The anaerobic and aerobic regions are separated by using a partitioning plate in the rectangular airlift bubble column rather than a draft tube, as the partitioning plate is more easily inserted into the existing tank.

4.1.2. Radial anaerobic–aerobic immobilized biomass (RAAIB) reactor

Immobilized biomass reactors can be applied as an alternative technology for wastewater treatment that combines anaerobic and aerobic processes. Systems with immobilized biomass facilitate the use of more compact units operating without recirculation and separation systems. The effective control of cellular retention time, the possibility to achieve high biomass concentration and, consequently, the application of low hydraulic retention time are advantages that have stimulated the adoption of immobilized biomass technology [75].

A bench-scale radial anaerobic/aerobic immobilized biomass (RAAIB) reactor packed with polyurethane foam cubes was developed, with the aim of removing both organic matter and ammonium nitrogen from sanitary wastewater with average feed COD content of 345 mg/L. The reactor achieved an organic removal efficiency of 84% at HRT of 1.2–15.5 h [68].

As shown in Fig. 9, the RAAIB reactor is divided into five concentric chambers. The influent wastewater is fed at the top of the first chamber and flows radially from the anaerobic to the aerobic section. The second and fourth chambers are packed with 10-mm-sided polyurethane foam cubes. The second chamber is designed for anaerobic process and inoculated with anaerobic sludge while the fourth chamber is not. The third aerobic chamber contains eight porous stones which are distributed uniformly close to the bottom of the reactor and connected to a compressor to aerate and mix the wastewater. Finally the effluent is discharged from the bottom of the fifth chamber.

This configuration favors the transfer of oxygen to the liquid mass attributable to the fixed polyurethane foam bed arrangement in concentric chambers, and the reactor is easy to operate and control which make it suitable as an attractive option.

4.1.3. Simultaneous aerobic–anaerobic (SAA) bioreactor system

The simultaneous aerobic–anaerobic (SAA) bioreactor as shown in Fig. 10 is a combination of air lift reactor, fluidized bed and upflow anaerobic sludge blanket. There are an inner cylinder and an outer cylinder in the bioreactor, and the aerobic and anaerobic zones are established by controlling aeration location, aeration capacity and reactor shape. The aerobic zone is formed in the inner cylinder, as air is supplied from the bottom of the bioreactor. The anaerobic zone is formed in the outer cylinder due to limited oxygen transfer from the central region. The influent flows into the bottom of the bioreactor, and the resulting effluent is withdrawn from the top of the bioreactor. There is a decrease of dissolved oxygen concentration in the down flow zone as water flows from the inner zone to the outer zone; under oxygen-limited condition, aerobic and anaerobic process occurs simultaneously as a result of dissolved oxygen concentration gradients arising from diffusion limitations [76].

The treatment of diluted landfill leachate wastewater with COD concentration varied from 1000 to 3300 mg/L was carried out in a

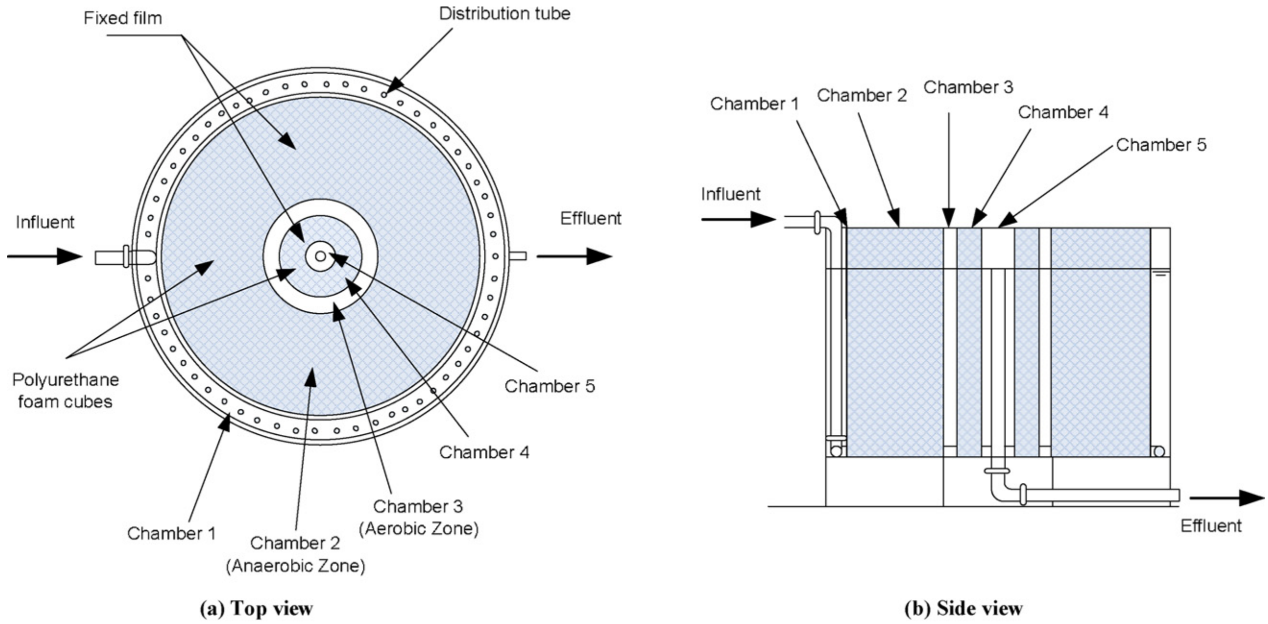

Fig. 9. Schematic diagram of the RAAIB reactor a) Top view; b) Side view [68].

SAA bioreactor system [70]. The reported COD removal efficiency ranged from 85 to 95%, with average removal efficiency of 94%.

The SAA bioreactor system is superior to conventional biological process for the effective removal of organic and nitrogenous matter from landfill leachates due to the reduced space requirement and operation management. Energy consumption is mainly utilized for the pump and air compressor and chemicals are rather rarely applied. Due to the simple operation and maintenance, the SAA bioreactor system is a good option for wastewater treatment, particularly in the developing countries.

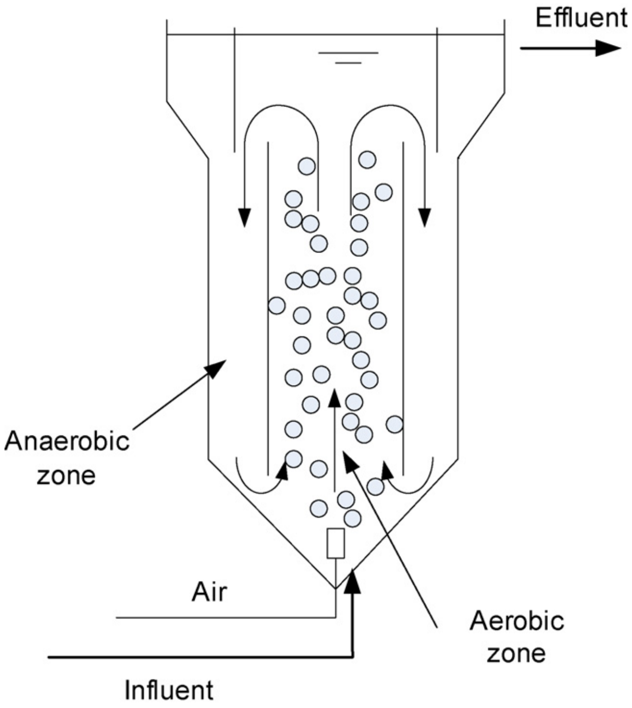

Fig. 10. Schematic diagram of the SAA bioreactor system [70]. (Reprinted from Chemosphere, The biological treatment of landfill leachate using a simultaneous aerobic and anaerobic (SAA) bio-reactor system, 72 (2008) 1751–1756, with permission from the copyright holders, Elsevier).

4.1.4. Anaerobic–aerobic integrative baffled bioreactor

An anaerobic–aerobic integrative baffled bioreactor was proposed for the treatment of potato starch processing wastewaters with COD values ranged from 1100 to 4500 mg/L [67]. In order to increase the efficiency, porous burnt-coke particles, a waste product of heavy industry is utilized as carriers in the aerobic zone to support the growth of microorganisms. With the presence of burnt-coke particles, the maximum COD reduction achieved was 98.7% while it was 96.0% in the absence of the burnt-coke. Burnt-coke carriers provide larger surface area for the attachment of the biofilm which leads to an increase in biomass concentration. The higher the biomass concentration in the carrier, the more organic matter was removed. An optimal HRT ranged from 12 to 24 h was used to produce effluent which was suitable for discharge.

The anaerobic–aerobic integrative baffled bioreactor is shown in Fig. 11 and includes three anaerobic zones, two depositions and one aerobic zone. It is rectangular and is subdivided equally into down flow and upflow sections by a series of 5-mm thick vertical high/low baffles. Due to the 45° turn out angle, the baffles cause the wastewater to rise and then flow downwards into the reactor. The system is divided into a three phase anaerobic biodegradation process. The first and second anaerobic zones are designed for hydrolysis, while the third anaerobic zone is mainly responsible for the production of methane. Depositions are designed for sedimentation and their main function is to separate the anaerobic and aerobic zone so that the anaerobic conditions are maintained in the anaerobic zones.

The advantages of this bioreactor include rapid biodegradation, low yields of sludge and excellent process stability. This configuration is an effective solution to the treatment of wastewater for most small and medium-sized plants which possess little economic capacity to invest in environmental controls. Based on its influent COD, anaerobic COD removal percentage and theoretical conversion yield of methane gas (0.38 m^3CH_4/kg COD), it is estimated that a total of 1.23 tonnes CH_4/L influent wastewater can be produced in this bioreactor. It should be noted that 21 CERs, which is equivalent to €210 can be claimed and generated as revenue if 1 tonne of methane gas produced in the bioreactor are captured as renewable gas, based on carbon credit price of €10 per tonne of carbon [77]. Hence, in this case, approximately €260 per litre influent wastewa-

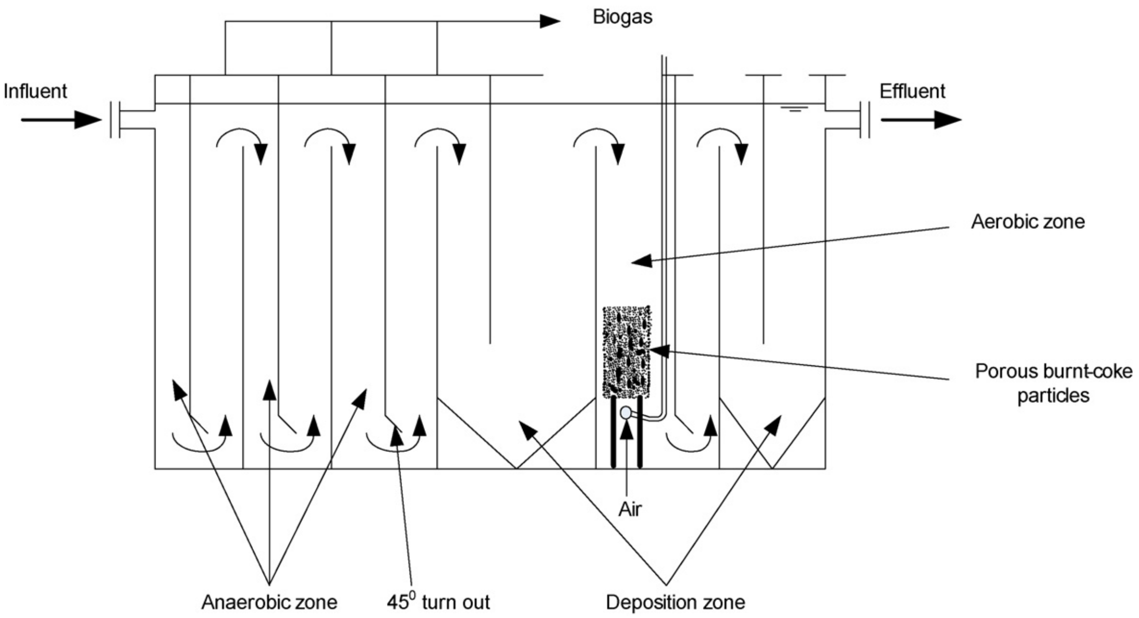

Fig. 11. Schematic diagram of the anaerobic–aerobic integrative baffled bioreactor [67]. (Reprinted from Chemical Engineering Journal, Efficiency of porous burnt-coke carrier on treatment of potato starch wastewater with an anaerobic-aerobic bioreactor, 148 (2009) 35–40, with permission from the copyright holders, Elsevier).

ter is highly potential of being awarded, which in turn will shorten the payback period on the investment of the bioreactor.

4.2. Integrated bioreactors without physical separation of anaerobic and aerobic zones

While the previous section covered anaerobic–aerobic treatment systems with separation between each process, a number of integrated bioreactors have been developed which allow the co-existence of anaerobic and aerobic populations inside the same reactor. This is done without physical separation using stacked configurations in which anaerobic conditions are maintained in the lower section while aerobic conditions are maintained in the upper part. This is achieved by introducing aeration at an intermediate height within the reactor [66,78–84] and Table 4 lists the systems based on this approach.

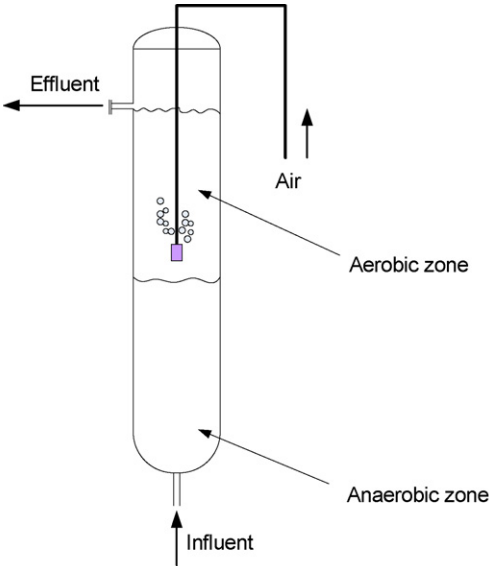

Fig. 12. Schematic diagram of combined UA/AFB integrated reactor system [84].

4.2.1. Upflow anaerobic/aerobic fixed bed (UA/AFB) integrated bioreactor

A bench scale upflow anaerobic/aerobic fixed bed (UA/AFB) integrated bioreactor as shown in Fig. 12 was developed and tested with synthetic wastewater. It is filled with PVC rings 1.5 cm in diameter as media and operated in an upflow mode that consists of two main zones: lower anaerobic zone and upper aerobic zone. Moosavi et al. [84] demonstrated that a total HRT of 9 h

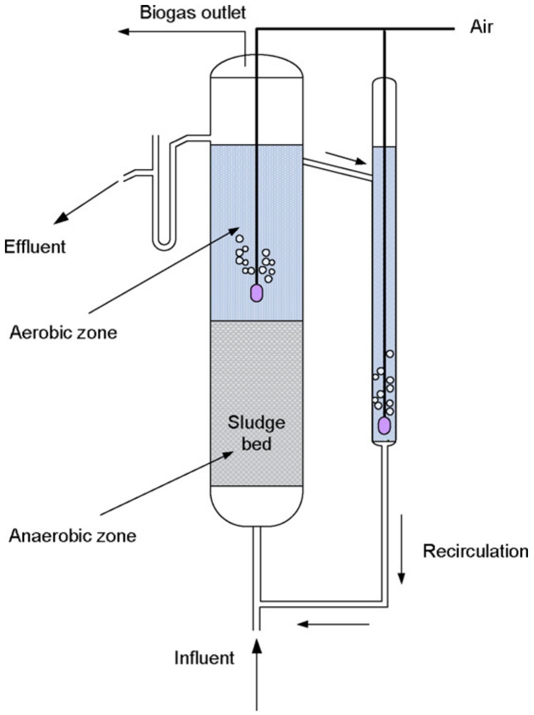

Fig. 13. Schematic diagram of anaerobic–aerobic granular biofilm reactor [66,78]. (Reprinted from Biochemical Engineering Journal, Degradation of trichloroethylene in a coupled anaerobic-aerobic bioreactor: Modeling and experiment, 26 (2005) 72–81, with permission from the copyright holders, Elsevier).

(5 h for anaerobic and 4 h for aerobic) is sufficient to accomplish efficient COD removal with more than 95% at OLR as high as 7.4 kg COD/m^3 d. The UA/AFB bioreactor is capable of handling high organic loads and able to recover immediately after any disturbances. The UA/AFB bioreactor is a potential biotechnology for treatment of industrial wastewater containing high organic loads. The study did not incorporate a methane gas capture system, which would produce biogas to partially offset the cost of treatment. It is projected that the bioreactor manages to attain approximately 20 carbon credit per liter of influent wastewater, which is equivalent to €200.

4.2.2. *Anaerobic–aerobic granular biofilm bioreactor*

Similar in design to a UA/AFB reactor, a granular biofilm bioreactor consists of an UASB with either an aeration column or a sparger placed in the middle part of the reactor. A schematic diagram of anaerobic–aerobic granular biofilm reactor is presented in Fig. 13. It has been utilized in the biodegradation of various chlorinated pollutants such as trichloethylene (TCE) [66,78] and polychlorinated biphenyl (PCB) [82]. The biodegradation of various chlorinated pollutants is based on the co-existence of aerobic methanotrophic and anaerobic methanogenic bacteria in a biofilm under oxygen-limited conditions.

Oxygen consumption by aerobic bacteria results in a steep oxygen gradient across the biofilm, leaving the interior a sufficiently thick biofilm free of oxygen and thereby provides a suitable niche for the growth of anaerobic methanogenic bacteria. Simultaneously, methane produced by the methanogens combined with the presence of oxygen favors the growth of aerobic methanotrophic bacteria in the outer layer of the biomass granules. Thus, anaerobic and aerobic populations of the biofilm co-exist closely in the same reactor system. It is a good strategy since both reductive and oxidative biotransformation occurs concomitantly to complete mineralization of highly substituted compounds under microaeration.

UASB reactors can accommodate low concentrations of oxygen without detrimental effects on the integrity or metabolic activity of the granular biomass. Thus, a partially aerated UASB reactor contains the substrates required by methanotrophic bacteria (i.e., indigenously produced methane and exogenously added oxygen) and could be an ideal system for maintaining consortia composed of methanogens and methanotrophs [78].

Shen and Guiot [79] investigated the impact of influent dissolved O_2, on the characteristics of anaerobic granular sludge at various dissolved O_2 concentrations (0.5–8.1 mg/L) via laboratory-scale anaerobic–aerobic granular biofilm bioreactor with a synthetic wastewater (carbon sources containing 75% sucrose and 25% acetate). As the granules are able to maintain good methanogenic activities when dissolved O_2 is present in the recirculated fluid, it indicates that the anaerobic–aerobic granular biofilm bioreactor can be successfully operated to maintain both active strict anaerobes and aerobes at the same time. With the elevated influent dissolved O_2, the methane yield declined from 64 to 42% of influent COD while the CO_2 generation rate rose from 0.23 to 0.39 L(CO_2)/g COD, suggesting more organic substrate was aerobically mineralized under high dissolved O_2 conditions. However, in spite of significant aerobic COD elimination in the coupled reactors receiving high dissolved O_2 influent, a major part of the influent COD (at least 62%) was anaerobically removed.

However, the presence of dissolved O_2 in the recirculated fluid resulted in fluffy biolayers on the granule surface, which imposed a negative impact on the settleability of granular sludge and caused a slightly higher sludge washout. The negative impact of influent dissolved O_2 on the granule structure and settleability represent a drawback for the practical operation of the reactor.

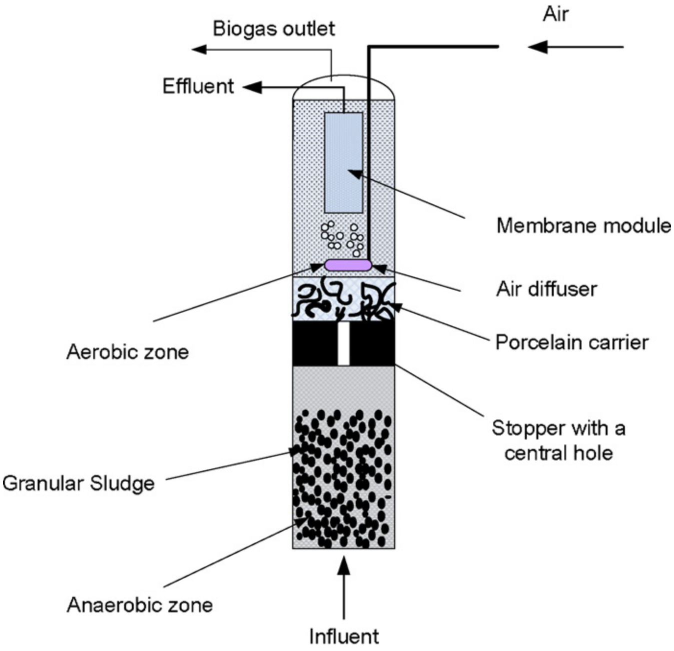

Fig. 14. Schematic diagram of staged anaerobic–aerobic MBR [83]. (Reprinted from Process Biochemistry, The integration of methanogensis with simultaneous nitrification and denitrification in a membrane bioreactor, 40 (2005) 541–547, with permission from the copyright holders, Elsevier).

4.2.3. *Staged anaerobic–aerobic membrane bioreactor (MBR)*

A staged anaerobic–aerobic membrane bioreactor (MBR) in which the membrane module is submerged in the aerobic zone is shown in Fig. 14 [83]. The aeration from the diffuser in the aerobic zone with the membrane module serves three purposes which are (i) providing oxygen for the biodegradation of substrates, (ii) mixing of the aerobic tank, and (iii) producing turbulence desirable to membrane cleaning. Porcelain carriers are installed to prevent the blockade of the orifice between the two zones of the reactor.

It has been employed successfully in the treatment of high strength synthetic wastewater containing high concentrations of ammonium with COD up to 10,500 mg/L and NH_4^+-N up to 1220 mg/L. The removal of the ammonium nitrogen from the high strength synthetic wastewater was accomplished through intermittent aeration in the aerobic zone, resulting in favorable conditions for the simultaneous nitrification and denitrification. The reported COD removals were exceeding 99% for OLR up to 10.08 kg COD/m^3 day. Between 60 and 80% of COD was anaerobically biodegraded in the anaerobic zone of the reactor and converted to methane that could serve as a carbon source for the denitrification in the aerobic zone. However, if the methane gas is captured as renewable energy, it is estimated that approximately 15 CER per liter of influent wastewater can be attained.

4.2.4. *Integrated anaerobic–aerobic fixed-film reactor (FFR)*

An integrated pilot-scale anaerobic–aerobic fixed-film reactor (FFR) with arranged media, developed by Del Pozo and Diez [81], exhibited high performance on the removal of organic matter from slaughterhouse wastewater. Overall organic matter removal efficiencies of 93% were achieved for an average OLR of 0.77 kg COD/m^3 day at HRT of 0.94–3.8 days. It should be pointed out that the integrated anaerobic–aerobic FFR achieves higher treatment efficiency than the anaerobic–aerobic FFB system described in Section 3.4.

The anaerobic–aerobic FFR, shown in Fig. 15, consists of vertically oriented corrugated tubes while air is supplied using five independent membrane diffusers. The reactor is divided into two

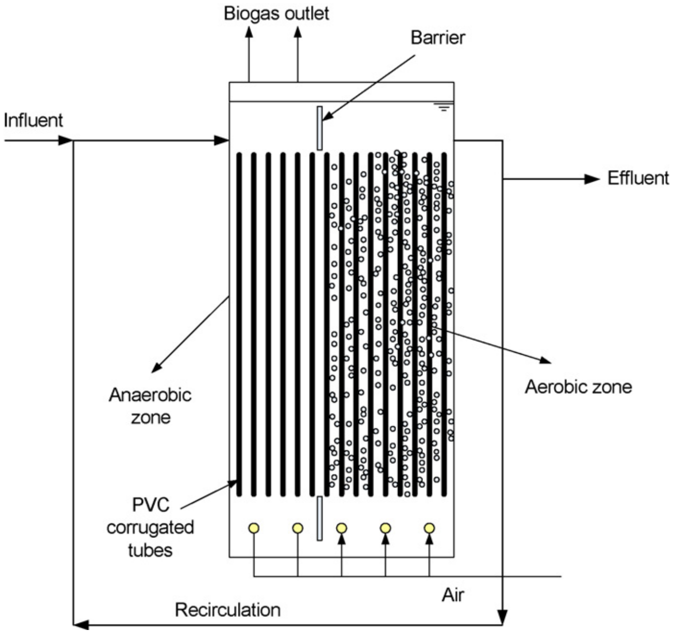

Fig. 15. Schematic diagram of integrated anaerobic–aerobic FFB [85]. (Reprinted from Water Research, Integrated anaerobic-aerobic fixed-film reactor for slaughterhouse wastewater treatment, 39 (2005) 1114–1122, with permission from the copyright holders, Elsevier)

compartments, the aerobic zone (with aeration) and the anaerobic zone, without physical barriers. Wastewater enters the system from the upper part of the non-aerated region, through which it circulates downwards before being entrained up through the aerated zone due to the air-lift effect of the air injection. It then leaves the reactor from the upper part of the aerobic zone. Different anaerobic–aerobic volume ratios (V_{an}:V_{ae}) are achieved by turning on and off each diffuser at the bottom of the reactor.

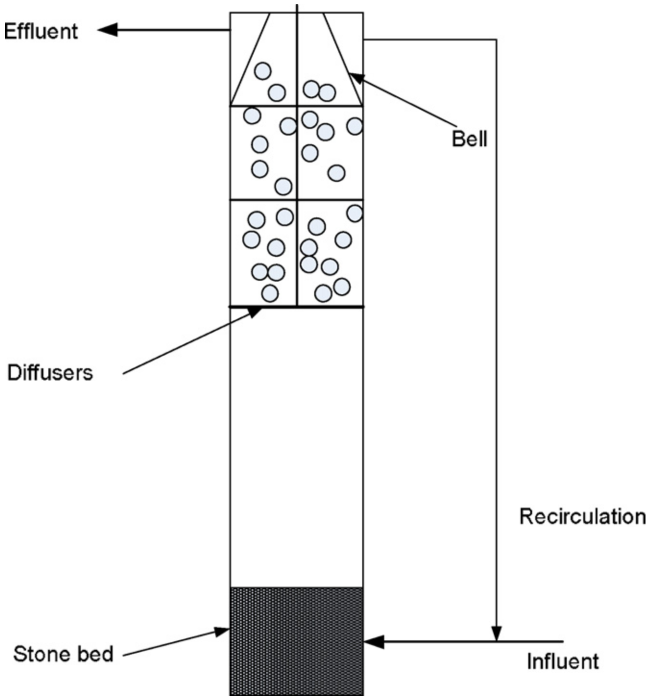

Fig. 16. Schematic diagram of integrated anaerobic–aerobic fluidized reactor [80]. (Reprinted from Water Science & Technology, 29 (10–11), 339–346, with permission from the copyright holders, IWA).

Most of the COD was removed through aerobic oxidation (96%), while the anoxic removal stood only for 2.6% and the methanogenic removal stood for 1.2% (V_{an}:V_{ae} was 3:2). When this ratio was reduced to 2:3 the COD removed by methanogenesis decreased to 0.6%. The main reason for the low extension of the anaerobic process is the high mixing pattern existing in the integrated reactor. High recirculation homogenizes the aerated and non-aerated zones, maintaining dissolved oxygen concentrations of 1.4 mg/l in the non-aerated zone. This significantly limits both the methanogenic and anoxic processes. Similar phenomenon was also reported by other authors working with bubble columns described in Section 4.1.1. [69] and it is important to clearly separate the aerated and non-aerated zones that allow strict anaerobic conditions to appear. This is the reason for the inclusion of the two small barriers seen in Fig. 15 at the top and at the bottom of the reactor. To recover the methane without dilution in the injected air, the aerated and non-aerated regions are set in parallel rather than in series.

4.2.5. Integrated anaerobic–aerobic fluidized bed reactor

Fdez-Polanco et al. [80] used a pilot scale anaerobic–aerobic fluidized bed reactor for the simultaneous elimination of organic carbon and nitrogen from municipal wastewater. Appreciable COD removal efficiencies (higher than 80%) were obtained at HRT of 24 h for an OLR of 1.2 kg COD/m^3 day.

Fig. 16 illustrates in schematic form the integrated anaerobic–aerobic fluidized bed reactor. The bioreactor is a cylindrical fluidized bed with pulverised pumice-stone as support material, and the aeration is carried out by four cylindrical fine bubble membrane diffusers arranged in a cross shape. This system is supported by a 'bell' (at the top of the diagram in Fig. 16) and different anaerobic/aerobic volume ratios (V_{an}:V_{ae}) can be achieved by varying its height in the interior of the bed.

The main advantages they observed were good stability despite variations in the organic load, a short start-up time, good recovery after unforeseen circumstances (e.g. the lack of aeration) and the possible automation using inexpensive technology. The main drawbacks identified were the requirement of additional pumping to maintain the support material in suspension. With the aim of diminishing the total COD and TSS of the effluent, the loss of support material as well as the concentration of dissolved oxygen in the effluent, a solid separation system in the effluent and recirculation should be implemented.

4.3. Comparison of integrated anaerobic–aerobic bioreactor in industrial wastewater treatment

While most of the integrated bioreactors discussed in this paper have not been implemented in an industry setting, the results on a laboratory, bench or pilot scale shown in Tables 3 and 4 indicate they can be utilized to treat various types of industrial and municipal wastewater. They can deal with a wide range of COD concentration (ranging from 345 to 10,500 mg/L), and provide good quality effluent with at least 80% COD removal at HRT of 1.2 h to 3.8 days. However, biogas capture is not emphasized in those integrated bioreactors due to the uncertainties related to corrosive behavior of the biogas and lack of technical expertise. Additionally, some of the integrated bioreactors utilize biogas constituents as electron donor for denitrification instead of harnessing the generated biogas as renewable energy. The staged anaerobic–aerobic membrane bioreactor achieves the best COD removal (more than 99%) at high OLR and short HRT. However, while presenting the best performance it is considered a high cost from both a capital and operating perspective and suffers from problems associated with membrane fouling thereby frequent cleaning of the membrane is necessary.

The physical separation of anaerobic and aerobic zones provide a simplified design which aids construction, operation, control and maintenance when compared to equivalent bioreactors without physical separation. Separation also makes it easier to maintain strict anaerobic and aerobic conditions although it does lead to an increase in construction costs.

Using a stacked configuration in the design of integrated anaerobic–aerobic bioreactors is advantageous as it reduces space requirements, providing lower capital cost while maintaining excellent COD removal efficiencies of 95–98%. Furthermore, the biogas produced from the anaerobic zone can be captured as renewable energy from the intermediate height of the bioreactor with a stacked configuration, ensuring the methane produced is not oxidized in the aerobic zone. The use of a packing medium can also provide strict anaerobic and aerobic conditions to reduce the negative impacts of dissolved O_2 on the anaerobic granule sludge [79]. The addition of biomass to the small suspended medium in the integrated bioreactor allows sludge with high settling velocity and high biomass concentration which leads to a low-volume bioreactor. This permits compact integrated reactors and completely closed conditions.

4.4. *Anaerobic–aerobic sequencing batch reactor (SBR)*

Conventional sequencing batch reactor (SBR) treatment systems generally consist of the batch steps of fill, react, settle, decant and idle in a cyclic operation with complete aeration during the react period to oxidize the organic matter and nitrify the ammonium-nitrogen of wastewater. Recently, SBR systems have been modified by adjusting the steps in the react cycle to provide anaerobic and aerobic phases in certain number and sequence for biological nutrient (C, N, and P) removal.

Most of the anaerobic–aerobic SBR systems are exploited in the treatment of textile wastewater for efficient color and COD removal [15,85,86]. The enrichment of desired microbial population can be accomplished easily by alternating anaerobic–aerobic phases through the control of the aeration in the anaerobic–aerobic SBR system. The duration, oxygen concentration, and mixing can be altered according to the needs of the particular treatment plant. In the operation of an anaerobic–aerobic SBR, pure nitrogen gas is purged in the anaerobic phase while air is supplied in the aerobic phase.

Investigations have been done to observe the effects of anaerobic–aerobic residence time on the performance of SBR. The experimental results indicated that anaerobic and aerobic residences times in SBR system significantly affected the system's performance. In the textile wastewater treatment, a slightly higher COD removal of 90% with an anaerobic/aerobic cycle of 17.5/2.5 h was achieved compared to COD removal of 87% with an anaerobic/aerobic cycle of 14/6 h. It was found that the duration of the anaerobic phase should be long enough to obtain better COD and color removal [87].

Kapdan and Oztekin [86] showed similar results in the treatment of textile synthetic wastewater. The optimum anaerobic and aerobic residence times were determined as 12 and 11 h respectively with total reaction time of 23 h for efficient overall COD removal (more than 85%). When aerobic residence time ((${}_{\text{Haerobic}}$) is 19–20 h, COD removal efficiency was around 50% under anaerobic conditions and reached to about 80% by the contribution of the aerobic phase to COD removal. However, as the anaerobic residence time was increased, the contribution of aerobic phase on COD removal was negligible. This was the result of the toxic effect of the dyestuff biodegradation end products of the anaerobic phase. Due to the batch operation, these were accumulated in the system and long term exposure of the cultures to these products inhibited aerobic organism activity. While transition between anaerobic to aerobic phases restrains the growth of aerobic organisms, the facultative anaerobic culture needs longer aeration period to be active under aerobic conditions.

On the other hand, appreciable soluble COD and BOD_5 removal efficiencies of 85 ± 6% and 95 ± 4% were achieved respectively in the treatment of wool dyeing effluents. The optimum residence times are 8 h anaerobic reaction and 12 h aerobic reaction with total cycle of 24 h in fast filling mode. Results indicated a longer aeration time resulted in better performance, due to more efficient cell growth and COD combined with a fast fill that provided the feast-famine conditions that favored sludge settleability. However, a long aeration period is not feasible in the form of operational economy [85].

Anaerobic–aerobic SBR has proved to be a suitable technology for organic removal from textile wastewater as high COD removal of more than 85% is achieved. Hence, anaerobic–aerobic SBR shows great potential in the treatment of high strength industrial and municipal wastewater due to their simplicity in operation. However, further investigations on its control of anaerobic–aerobic microbial consortia, methanogenic activity, biomass yield and its ability to recover from shock organic loads are required.

4.5. *Integrated bioreactor based on combined anaerobic–aerobic cultures*

Combined culture is the mixture of anaerobic and aerobic cultures that could survive under alternating anaerobic–aerobic conditions in the same reactor. Methanogenic and aerobic biological processes are often considered mutually exclusive and separated as biological wastewater treatment options. Dissolved oxygen (DO) even at low levels is considered to be extremely toxic to methanogens. Nonetheless, they have been found to survive short periods in the presence of dissolved oxygen and coexist with aerobic or microaerophilic organisms in a single mixed culture. The survival of anaerobic cultures under aerobic or microaerobic

Table 5
Advantages and disadvantages of various types of integrated anaerobic–aerobic bioreactors.

Bioreactor Type	Advantages	Disadvantages
Integrated bioreactors with and without physical separation of anaerobic–aerobic zone	High organic removal efficiency	Complicated design of bioreactor
	Capable of handling high OLR	Relatively higher construction cost
Anaerobic–aerobic SBR	Single tank configuration without the need of clarifier	Complex control of anaerobic–aerobic microbial consortia
	Low capital cost	Require special attention to determine anaerobic and aerobic residence time
	Low energy requirement	High level of sophistication is required
	Flexibility in operation	
Combined anaerobic–aerobic culture system	Low energy requirement	Complex control of anaerobic–aerobic microbial consortia
	Small reactor volume	Sensitive to environmental condition

conditions (i.e. DO concentration < 1 mg/L) is due to the intrinsic tolerance or formation of anaerobic niches [88]. As a result, combined anaerobic–aerobic cultures have been investigated increasingly over the last two decades [88–96].

Combined cultures have been applied successfully in the treatment of several contaminants such as polycyclic aromatic hydrocarbons, and highly chlorinated solvents that require sequentially operated anaerobic and aerobic or anoxic reactors [90,94,95]. With free or co-immobilized cultures of anaerobes and aerobes, DO concentrations display alternating values. The oxygen gradient results in alternating conditions from aerobic to anaerobic either through the reactor content (as in packed bed or slurry reactors) or from bulk liquid to the depths of the immobilized cocultures. This leads to possible living conditions for different types of bacteria and makes the coexistence of anaerobic and aerobic cultures feasible. Interestingly, others have identified that with the addition of 4 mg O_2/L day to essentially anaerobic cultures, methane production has been doubled when algae was the primary substrate [97].

For low strength municipal wastewaters treatment, combined cultures from a mixture of anaerobic granular and suspended aerobic cultures (40:60, v/v) were developed in an upflow sludge bed (USB) reactors. The combined cultures in USB reactor exhibited average BOD removal efficiency of 52–76% at HRT of 0.75 day. Combined cultures which were aerated every other day (i.e. alternating cyclic anaerobic to microaerobic/aerobic conditions) were considered as the optimum and feasible aeration protocol as compared to aeration for 4 h/day or continuously due to their higher removal efficiencies, slightly better settling characteristic and lower oxygen requirement [88].

Appreciable COD removal efficiencies (greater than 93%) were reported in the study of sucrose biotransformation under methanogenic and oxygen-limited conditions in bench-scale batch reactors seeded with a mixture containing anaerobic digester sludge and aerobic mixed liquor. In addition to oxygen-limited reactors, anaerobic (methanogenic) and aerobic (dissolved oxygen greater than 2.0 mg/l) systems were operated in parallel for comparison. It was observed that the overall COD removal efficiencies for oxygen-limited cultures, strictly anaerobic cultures, and strictly aerobic cultures were comparable under the complete-mix, suspended growth conditions. The limited-aeration conditions were achieved by introducing air through a timer-actuated solenoid valve which was open for 15 seconds in every half-hour [91].

Integrated bioreactors containing anaerobic–aerobic cultures can be beneficial compared to conventional anaerobic and aerobic treatment system due to their achievement of required discharge standards, prevention of biomass loss, high settling characteristic, reduced aeration and additional methane production. Combined cultures are perceived as an energy efficient treatment alternative to achieve low final COD concentrations, minimal biosolids generation, and mineralization of a broad range of specific organic chemicals. Nonetheless, further research is required to address the application and process control issues of these types of bioreactor systems.

4.6. Overall comparison of the integrated anaerobic–aerobic bioreactors

The advantages and disadvantages of the four types of integrated anaerobic–aerobic bioreactors are presented in Table 5. The anaerobic–aerobic SBR and combined anaerobic–aerobic culture system require less energy input than either types of integrated bioreactors, as less aeration is required. However, inappropriate control of anaerobic and aerobic residences times in SBR system will result in difficulties controlling the anaerobic–aerobic microbial consortia and thus the selection and enrichment of the desired microbial population will be difficult to achieve. A high level of sophistication is required in timing units, controller, software and censors while automated switches and valves are required to achieve efficient organic removal in anaerobic–aerobic SBR system.

For combined anaerobic–aerobic culture system, control of aeration time and maintenance of oxygen limited condition in the bioreactor are critical as methanogens are sensitive to the presence of dissolved oxygen. Excessive dissolved oxygen concentration will restrain methanogenic activity and adversely affect the performance of the system.

Integrated bioreactors with and without physical separation of anaerobic–aerobic zone have exhibited the best performance in terms of COD removal and are capable of handling high OLR when compared to the anaerobic–aerobic SBR and combined anaerobic–aerobic culture system. However, the design and configuration of integrated bioreactor are more complicated and therefore, its construction cost inevitably would be higher than anaerobic–aerobic SBR system and combined anaerobic–aerobic culture system. With proper installation of methane gas capturing system, integrated anaerobic–aerobic bioreactor emerges as a viable technology in treating high strength industrial wastewaters, in which it offers an attractive energy recovery source while reducing greenhouse gas emissions. This may in the future lead to it being awarded carbon credits from the Clean Development Mechanism (CDM), further shortening the payback period for investment.

5. Conclusion

Anaerobic–aerobic treatments receive great attention over the past decades due to their numerous advantages such as low energy consumption, low chemical consumption, low sludge production, vast potential of resource recovery, less equipment required and high operational simplicity. However, conventional anaerobic–aerobic systems are found to have operational limitations in terms of long HRT, space requirement and facilities to capture biogas. The applications of newly developed high rate bioreactors address these limitations and provide increased organic matter removal at shorter HRT and higher methane yields for biogas production.

In order to meet strict constraints with respect to space, odors and minimal sludge production, considerable attention has been directed towards the integrated anaerobic–aerobic bioreactors which combine the aerobic and anaerobic process in a single bioreactor. With simple yet cost effective technology, the generation of renewable energy and outstanding treatment efficiency, it is envisaged that the compact integrated bioreactors will be able to treat a wide range of high organic strength industrial and municipal wastewater. However, most of the integrated bioreactors reported in this work lack large scale implementation within industry and further work is required to evaluate the performance of these promising reactors on a larger scale. Besides, further improvements such as installation of biogas capture system and utilization of suspended carrier or packing medium are considered essential.

As such, the integrated bioreactors can attain carbon credit derived from Clean Development Mechanism (CDM) under Kyoto Protocol 1997, shifting the paradigm of wastewater management from ‘treatment and disposal’ to ‘beneficial utilization’ as well as ‘profitable endeavor’.

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