



A Review on Different Aerobic and Anaerobic Treatment Methods in Dairy Industry Wastewater

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Abstract

Dairy industries have grown tremendously in many regions around the world due to the growth of demand for milk-related products. Dairy industries release wastewater containing high chemical oxygen demand (COD), biological oxygen demand (BOD), nutrients, in addition to organic and inorganic substances. Such wastewater, if improperly treated, severely pollutes water resources. For many years, anaerobic-aerobic processes have been used to remarkable effect in the treatment of dairy industry wastewater. Previously, a large portion of wastewater treatment was carried out in conventional anaerobic-aerobic treatment units. Nowadays, high-rate anaerobic-aerobic bioreactors are progressively employed for treating wastewater with high COD content. This paper reviews dairy wastewater sources, their production, and their characteristics. Furthermore, different types of high-rate anaerobic-aerobic wastewater treatment methods currently available, including aerobic and anaerobic bioreactors over and above hybrid anaerobic-aerobic bioreactors, are discussed. The strong points and the weaknesses of different individual and combined anaerobic and aerobic bioreactors are highlighted; they are then compared to point out future areas of investigation for full usage and application of these methods for wastewater treatment. The comparison demonstrates that using an integrated bioreactor is advantageous in treating highly polluted industrial wastewater. The combination of aerobic and anaerobic degradation pathways in an individual bioreactor can enhance overall degradation efficiency. Furthermore, this combination appears as an attractive alternative from the technical, economic, and environmental perspectives, especially wherever space is a limiting factor.

Keywords: Dairy product, Industrial dairy wastewater, Anaerobic-aerobic treatment, Anaerobic-aerobic bioreactors, Wastewater treatment

1 Introduction

Nowadays, many environmental crises threaten human life (1-4). One of the most dangerous is the waste from the dairy industry and milk factories (5-10). Any effort to prevent environmental pollution from the expansion of the dairy industry and milk factories should take into account the effluents they produce (9, 11-15). Milk is the raw material of the dairy industry, regardless of whether the finished dairy product is fresh milk, powdered milk, or some other products. The quality and quantity of wastewater produced

vary significantly, depending on the product (16-18). Water pollution causes a sharp drop in dissolved oxygen. Compounds such as albumin, casein, lactose, and milk fat are highly biodegradable and decompose rapidly, becoming rancid and septic. Another main water pollutant from the dairy industry is whey (19-21). The liquid whey and the casein that remain in milk after fat removal are used to make cheese. In the milk clotting (coagulation) process, milk is separated into curd and whey by the action of milk clotting enzymes such as rennet or any edible acidic compound

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like lemon juice or vinegar. Clots (rennin curds) contain casein, fats, minerals, and vitamins, while whey contains lactose, soluble proteins, and/or whey proteins, enzymes, organic acids, water-soluble vitamins, and minerals (20, 22-27). From the economic and environmental point of view, whey disposal highlights itself as a thorny issue (28). The present rules and regulations executed by environmental bodies have had a significant positive impact on new technologies. This has resulted in enhancing the treatment of dairy products. Dairy product treatment methods are classified into four categories: chemical, physical, biological, and hybrid methods (which are also called mixed methods or multistage dairy product treatment systems). It is worthy of mentioning that by mixed [multistage] treatment here we mean a combination of aerobic and anaerobic methods. This classification is presented in Fig. 1. Cleaning of transport lines, equipment between production cycles, tank trucks, milk storage tanks, and equipment malfunctions as well as operational errors generate most of the wastewater in the dairy industry (29, 30). Wastewater of dairy industry is often treated utilizing coagulation/flocculation and sedimentation processes. The main drawbacks of these methods are their high coagulant cost, high sludge production, and poor removal of COD. Hence, biological treatment is typically recommended for treating dairy wastewater (31).

Anaerobic granular sludge sequencing batch reactor (SBR) was used by Schwarzenbeck et al. (32) for the treating of dairy industry wastewater. They presented COD, total nitrogen, and total phosphorus removal efficiencies of 90%, 80%, and 67%, respectively, at 8 h of hydraulic retention time (HRT). Kushwaha et al. (33) employed an SBR in order to remove COD and nitrogen from dairy wastewater: they obtained COD and total Kjeldahl nitrogen (TKN) removal efficiencies of 96.7% and 76.7%, respectively at an HRT of 24 h. Sirianuntapiboon et al. (34) used an SBR biofilm system for milk industry wastewater treatment. They presented 97.9% and 79.3% removal efficiencies of COD and TKN, respectively at an organic loading rate of 680 g biological oxygen demand (BOD_5)/ m^3d . A study by Omil et al. (35) demonstrated that an anaerobic filter reactor (AFR) coupled with an SBR can achieve a COD removal efficiency of over 90% at an organic loading rate of 5–6 kg COD/ m^3d . An upflow anaerobic sludge blanket (UASB) bioreactor was applied for the treatment of wastewater from the cheese production industry. The COD removal efficiency thereof 96% was obtained at an HRT and organic loading rate of 5.3 h and 10.4 g COD/l d, respectively (36). In addition, a membrane SBR was used to treat dairy industry wastewater. Thence, high-quality effluent results were obtained at 12 h HRT with BOD, total suspended solids, total nitrogen, and total phosphorus removal at 97-98%, 100%, 96%, and 80%, respectively (37).

Several recent qualified, comprehensive research and review papers were published with emphasis on different topics of the aerobic/anaerobic biological treatment methods which are discussed in the next sections.

2 Characteristics of the dairy effluents

Dairy industry wastewater is generally produced intermittently; therefore, effluents' flow rates alter significantly. Wide seasonal variations are also frequent and related to the volume of milk received for processing, which is usually high in summer and low in winter (38). In general, the dairy industry produces lots of wastewaters—nearly 0.2–10 L of waste per liter of processed milk (39-41). Given that the dairy industry generates various products, such as milk, butter, yogurt, ice-cream, and different desserts, the characteristics of dairy industry effluents also change significantly based on the operation techniques used in this process (31). Wastewater characteristics in the dairy industry affected by using acid and alkaline cleaners and sanitizers generally lead to a highly variable pH (29, 42-44). In literature, information on the dairy wastewater characteristics of full-scale operations is rare. To the best of our knowledge, only one study has been published, which presents wide information on the specific characteristics of dairy wastewater from several full-scale operations (29). Figs. 2 and 3 are some indications that a comprehensive review in this field is next to necessary to draw general conclusions and provide some guided perspectives for future research. This is despite the fact that a few reviews involving related topics of aerobic/anaerobic biological treatment of dairy wastewater have appeared recently (40, 45). Many researchers have turned their attention to anaerobic treatment methods more than aerobic methods; in point of fact, as indicated by the number of citations per year, interest is still growing (see Figs. 2 and 3) (46, 47).

In general, aerobic and anaerobic processes can be applied for treating dairy wastewater in order to obtain a high level of organic removal efficiency. Nonetheless, these processes suffer from a number of restrictions that reduce their effectiveness. Aerobic processes are commonly used for treating low-strength effluents (biodegradable COD contents lower than 1000 mg/L) while anaerobic processes are commonly used for treating highly polluted effluents (biodegradable COD contents greater than 4000 mg/L) (48). A comparison of aerobic and anaerobic processes is presented in Table 1. The high energy demands of aerobic treatment systems are the biggest disadvantage of these processes. Furthermore, dairy wastewater is warm and highly polluted, providing an ideal condition for anaerobic treatment. Moreover, no demand for aeration, the minor level of excess sludge generation, and low area requirement are additional advantages of anaerobic treatment processes (in comparison to aerobic processes). The stated positive points prompted the fast development of biological systems for treating dairy industry wastewater using conventional anaerobic-aerobic treatment plants or high-rate bioreactors were developed to reduce the capital cost of the process. However, the investigation of high-rate anaerobic-aerobic treatments is limited and not well documented. Therefore, the main objective of this review is to summarize and discuss the feasibility of high-rate anaerobic-aerobic treatment methods for removing organic compounds from the wastewater of the dairy industry. Additionally, the characteristics and sources of dairy wastewater are discussed in this review.

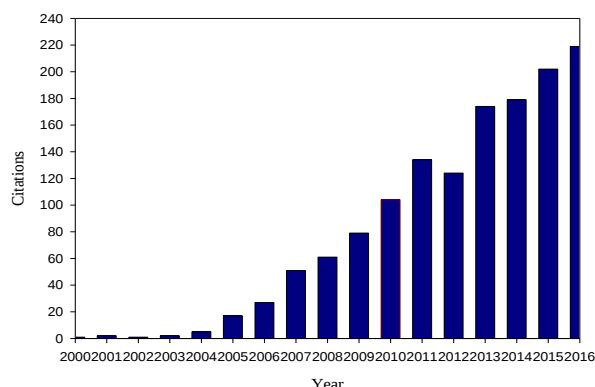


Fig. 2: Citations on “aerobic treatment of dairy wastewater” per year, showing the increasing research interest in this topic. Data from ISI Web of Knowledge, Thomson Reuters.

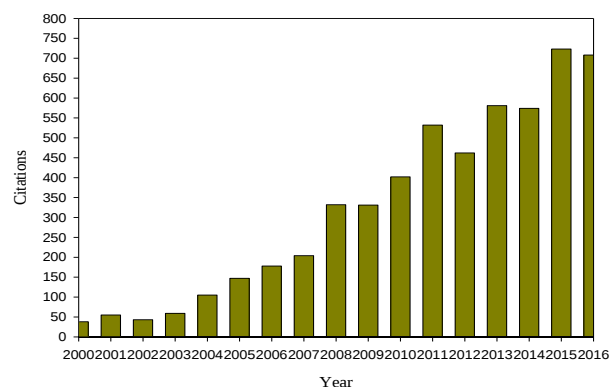


Fig. 3: Citations on “anaerobic treatment of dairy wastewater” per year, showing the increasing research interest in this topic. Data from ISI Web of Knowledge, Thomson Reuters.

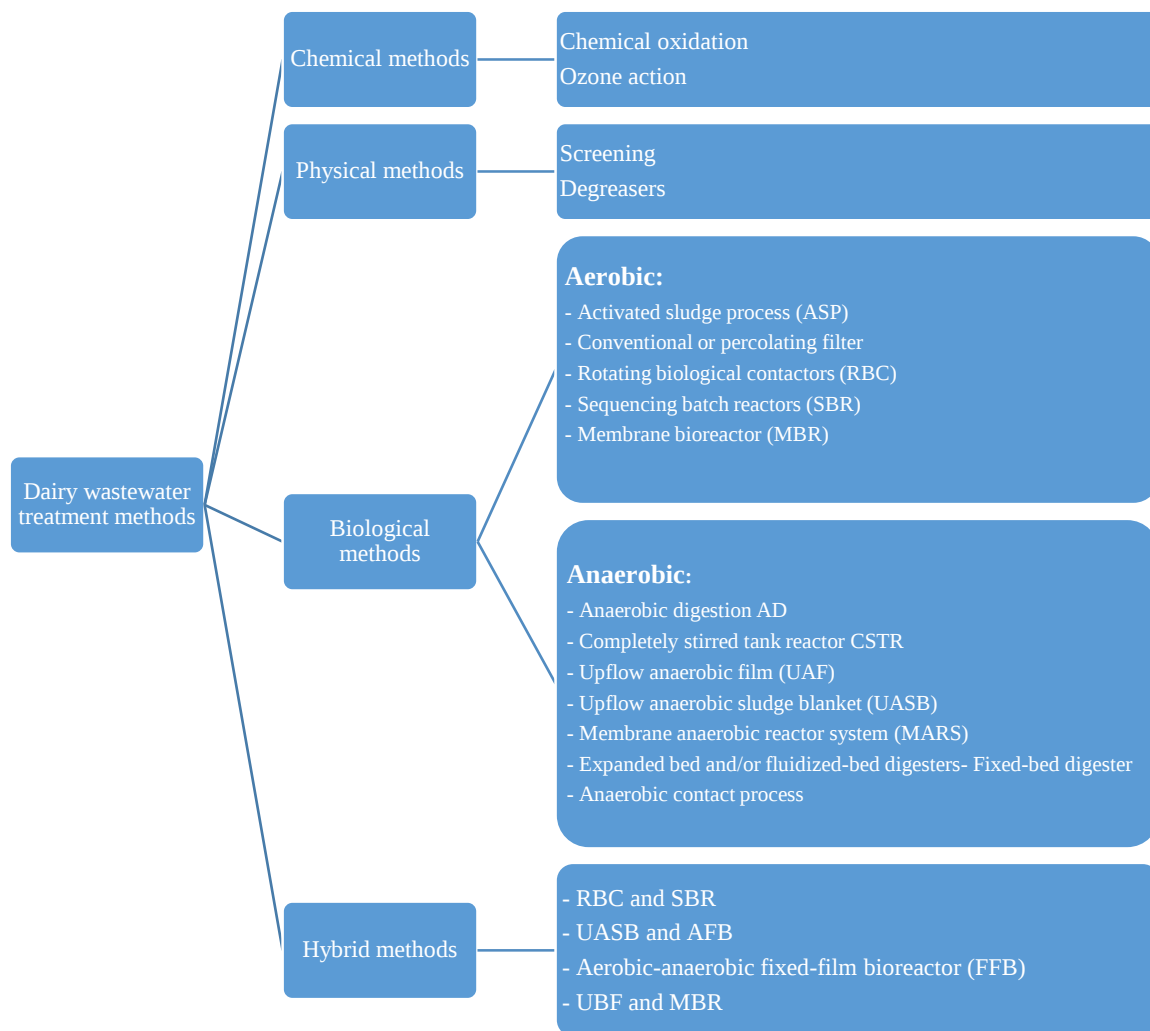


Fig. 1: Classification of dairy wastewater treatment methods.

Table 1: Comparison of aerobic and anaerobic treatment methods (48-51).

Feature	Aerobic	Anaerobic
Organic removal efficiency	High	High
Wastewater quality	Great	Moderate to poor
Organic loading rate	Moderate	High
Sludge generation	High	Low
Nutrient demand	High	Low
Alkalinity demand	Low	High for certain industrial waste
Energy demand	High	Low to moderate
Temperature sensitivity	Low	High
Odor	Less opportunity for odors	Potential odor problems
Bioenergy and nutrient recovery	No	Yes
Mode of treatment	Total (rely on feedstock characteristics)	Essentially pretreatment

General characteristics of dairy waste effluents from full-scale operations are summarized in Table 2 (52-60). High COD contents demonstrate that the wastewater of the dairy industry is highly polluted and fluctuates in nature. Considerable amounts of the organic compounds and nutrients in dairy wastewater are obtained from milk and milk products. Nitrogen is mainly derived from milk proteins in the wastewater of the dairy industry. It is presented in different forms, either as organic nitrogen (i.e., proteins, urea, and nucleic acids) or as ions (i.e., NH_4^+ , NO_2^- , and NO_3^-). The common forms of phosphorus are inorganic like orthophosphate (PO_4^{3-}) and polyphosphate ($\text{P}_2\text{O}_7^{4-}$), though there are organic phosphorus forms present, too (61). Other methods that can be utilized to measure wastewater pollution level and treatability are concentrations of suspended solids (SS) and volatile suspended solids (VSS) (29). SS in wastewater of the dairy industry is derived from coagulated milk, cheese curd, or flavoring ingredients (62). Concentrations of selected elements, including sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), cobalt (Co), nickel (Ni), and manganese (Mn), are listed in Table 3. In particular, high Na concentrations signify the extensive utilization of alkaline cleaners in dairy industries. The concentrations of heavy metals including copper (Cu), nickel (Ni), and zinc (Zn) were reportedly low enough not to adversely affect the performance of biological treatment (29, 52). Wastewater of dairy industry is simply made of degradable carbohydrates, mainly lactose; and also less biodegradable proteins and lipids (63). In cheese factory wastewater, 97.7% of total COD was formed via compounds such as lactose, lactate, protein, as well as fat (55). As a result, dairy wastewater may be considered a complex substance (63-65). Lactose is the main carbohydrate in dairy wastewater and is an easily available substance for anaerobic bacteria. Lactose anaerobic methanation requires collaborative biological activity from acidogens, acetogens, and methanogens (66). Components such as organic acids, namely, acetate, propionate, iso- and normal- butyrate, iso-, and normal valerate, caproate, lactate, formate, and ethanol can be produced from lactose anaerobic fermentation (67, 68). Kisaalita et al. (67) presented two methods of carbon flow for the acidogenic fermentation of lactose including carbon flow from pyruvate to butyrate and lactate, both taking place in parallel. The existence of high carbohydrate levels in synthetic dairy wastewater leads to some decrease in the synthesized proteolytic enzymes content, resulting in low content of protein degradation (63). Carbohydrates were

reported to be capable of suppressing the synthesis of exopeptidases, a collection of enzymes assisting protein hydrolysis (69). The anaerobic degradation of proteins mechanism and the impact of ammonia on this process were studied in detail by researchers (70-74). The main protein in milk composition and dairy wastewater is casein. Casein degrades quickly while fed to acclimated anaerobic reactors: the consequence degradation products of this mechanism are non-inhibitory (75). Lipids are basically inhibitory compounds produced during dairy effluent anaerobic treatment. Existing literature has limited information on the lipids anaerobic digestibility. Lipids are hydrolyzed to glycerol and long chain fatty acids (LCFAs) during anaerobic degradation process, followed by β -oxidation. This produces acetate and hydrogen (69). Low bioavailability of lipids makes the mechanism of lipids biodegradation complicated (76). Glycerol obtained from lipid hydrolysis was found to be a non-inhibitory component (75), while LCFAs were presented to inhibit methanogenic bacteria (77). The inhibitory effect of lipids on anaerobic mechanisms can be associated with the existence of LCFAs, which postpone methane production (78). While lipids do not create crucial issues in aerobic processes, they sometimes adversely affect the typical processes of single-phase anaerobic treatment (79, 80). Saturated LCFAs reported having a lower inhibitory impact than unsaturated LCFAs. Unsaturated LCFAs actively inhibit methane generation from acetate and moderately inhibit β -oxidation. Consequently, it would be better to convert unsaturated LCFAs to saturated LCFAs in order to avoid lipid inhibition in anaerobic mechanisms (80). Difficulties experienced with lipids in anaerobic treatment processes have been presented in the literature (81-85).

3 Treatment technologies

3.1 Primary treatment (Screening, Degreasers)

The screen is used in wastewater treatment in order to eliminate large particles that may cause damage to pumps and blocking of downstream (86). For purposes of avoiding a further increase in COD content due to solid solubilization, physical screening of dairy wastewater should occur as fast as possible (87, 88). Wendorff (89) suggested the utilizing of a wire screen and grit chamber with a screen orifice size of 9.5 mm, whereas Hemming (87) suggested the employing of finer spaced, mechanically brushed, or inclined screens of 40 mesh (about 0.39 mm) for reducing solids.

Table 2: Characteristics of industry dairy wastewater.

Effluent type	COD (mg/l)	BOD ₅ (mg/l)	pH (units)	Alkalinity (mg CaCO ₃ /l)	Suspended solids (mg/l)	Volatile suspended solids (mg/l)	Total solids (mg/l)	TKN (mg/l)	Total phosphorus (mg/l)	Reference
Creamery	2000-6000	1200-4000	8-11	150-300	350-1000	330-940	—	50-60	—	(43)
Not given	980-7500	680-4500	—	—	300	—	—	—	—	(38)
Mixed dairy processing	1150-9200	—	6-11	320-970	340-1730	255-830	2705-3715	14-272	8-68	(42)
Cheese whey	68814a	—	—	—	—	—	—	1462a	379a	(56)
Cheese	1000-7500	588-5000	5.5-9.5	—	500-2500	—	—	—	—	(57)
Fresh milk	4656a	—	6.92a	—	—	—	—	—	—	(59)
Cheese	5340a	—	5.22a	—	—	—	—	—	—	(59)
Milk powder/butter	1908a	—	5.80a	—	—	—	—	—	—	(59)
Mixed dairy Processing	63100a	—	3.35a	—	12500a	12100a	53000a	—	—	(55)
Cheese whey	61000a	—	—	—	1780a	1560a	—	980a	510a	(60)
Cheese	—	—	4.7a	—	2500a	—	—	830a	280a	(54)
Not given	—	—	4.4-9.4	—	90-450	—	—	—	—	(53)
Fluid milk	950-2400	500-1300	5.0-9.5	—	90-450	—	—	—	—	(58)
Ice-cream	5200	2450	5.2	—	—	2600	3900	60	14	(90)
Ice-cream	4940	—	6.96	—	1100	990	—	—	—	(91)
Milk permeate	55200-63480	—	5.55-6.52	—	2670-3800	—	—	—	350-450	(92)
Milk processing	5000-1000	3000-5000	4-7	—	—	—	3000-7000	20-150	50-70	(93)
Dairy	4590	—	7.12	—	—	2100	4350	89	9.9	(94)
Dairy	2000-6000	1200-4000	8-11	—	350-100	330-940	—	50-60	20-50	(95)
Dairy	5000	2800	7.1	—	—	1350	3880	16.5	38.6	(96)
Cheese whey	60000	40000	4.46	—	—	1500	59000	—	—	(97)
Cheese whey	68600	7710	4.9	—	—	—	1350	1120	500	(98)
Dairy	3620	2115	8.5-10.3	—	647	1430	—	—	187	(99)
Milk processing	900-1200	640-850	6.8-7.2	—	40-50	—	—	—	48-52	(100)

^a Mean concentrations are presented.

Table 3: Concentrations of selected elements in dairy effluents

Effluent type	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)	Co (mg/l)	Ni (mg/l)	Mn (mg/l)	Reference
Creamery	170-200	35-40	35-40	5-8	2-5	0.05-0.15	0.5-1.0	0.02-0.10	(43)
Cheese/whey	735a	42.8a	47.7a	11.4a					(29)
Cheese/alcohol	423a	41.2a	54.3a	8.3a					(29)
Cheese/beverages	453a	8.6a	33.6a	16.9a					(29)
Cheese/whey	419a	35.8a	52.3a	11.0a					(29)
Mixed dairy	123-2324	8-160	12-120	2-97	0.5-6.7	0	0-0.13	0.03-0.43	(42)
Cheese	720-980		530-950						(57)

^a Mean concentration is reported.

As reported by Droste (86), to avoid the settling of coarse matter in wastewater, precautionary measures should be carried out before the screening. He recommends ensuring a 1:2 ratio of depth to width of the approach channel to the screen and water velocity not lower than 0.6 m/s. Screens ought to be cleaned out using manual or mechanical methods and screened material disposed of at a landfill site. After screening, fat, oil, and grease (FOG) compounds must be removed. Fat adheres to degreasers. Most pond FOG mass float to the water surface by gravity method and are manually removed (69).

In the case of a self-operating and easily-constructed system, wastewater flows across a series of cells, and FOG mass, generally floating on the surface, is separated by retention within the cells. Disadvantages comprise continuous monitoring and cleaning to avoid FOG buildup, as well as reduction of removal efficiency at pH higher than 8 (58). Occasionally, to facilitate this work in aeration ponds, air flotation and dissolved air flotation (DAF) is used to transfer fat particles to the surface and prevent mildew and odor production.

3.2 Major aerobic biological treatment methods

Wastewater treatment usually extends from physical treatment to biological treatment systems. Numerous studies were conducted on wastewater biological treatment. An aerobic biological treatment technique relies on microorganisms grown in an environment that is rich in oxygen to oxidize organic materials to CO₂, water, and cellular compound. Remarkable data on laboratory- and field-scale aerobic treatments confirmed that aerobic treatment is reliable and cost-effective for the production of high-quality effluent (101). Start-up typically needs an adjustment period to allow the expansion of a competitive microbial community. In this process, ammonia-nitrogen can be successfully removed to avoid disposal problems. Foaming and poor solid-liquid separation are common issues of aerobic processes. Many aerobic biological treatment techniques were developed to treat dairy production wastewater, such as activated sludge (AS), conventional or percolating filter, rotating biological contactor (RBC), sequencing batch reactor (SBR), and membrane bioreactor (MBR). The pros and cons of these methods are presented in Table 4.

3.2.1 Activated sludge process

As presented by Smith (102), a typical activated sludge process (ASP) is an ongoing treatment process that uses a group of microorganisms that are suspended in wastewater in an aeration tank to absorb, adsorb, and biodegrade organic pollutants. A simplified diagram of this process is shown in Fig. 4. A portion of the organic compound is effectively oxidized to innocuous end products and other inorganic matters to supply energy for the sustainable growing of microbial as well as the formation of biomass (flocs). Flocs are maintained in suspension by one of the air blown into the bottom of the tank or mechanical aeration methods. The dissolved oxygen content in the aeration tank is crucial and should be in the range of 3–5 mg/L. The duration of aeration, as well as cell residence time, has to be considered for designing an aeration tank. The mixture flows to a sedimentation tank from the aeration tank where the activated sludge flocs form larger particles that settle as sludge. The biological aerobic metabolism process produces large quantities of sludge (0.6 kg dry sludge per kg of BOD₅ removed). Certain sludge is recycled to the aeration tank; however, the remaining must be processed and disposed of in an environmentally sound manner, which is a major running cost. There are numerous alterations of ASP; yet in all cases, the main energy-consuming operation is providing oxygen during the aeration process. With ASPs, issues usually occurring are bulking (103-105), foam production, iron, and carbonates precipitation, extreme sludge production, as well as a decline in efficiency during winter. Various reports present that ASP has been employed to successfully treat wastewater of the dairy industry (105). Donkin and Russell (106) reported that reliable COD removal of over 90%, as well as TN decrement of 65%, could be achieved with milk powder and butter wastewater respectively. The removal of phosphorus compounds was less reliable and appeared to be sensitive to environmental variations.

In 2013, the effect of varying retention time was investigated in the AS system by Lateef et al. (107). The removal efficiencies of COD and BOD were 96% within five days (107). Increased retention time did not notably affect BOD₅ and COD removal. However, increasing retention time has several advantages. For example, longer retention time and aeration time result in uniformity in these ponds, in

which the action keeps the immune system from organic shocks. The second advantage is lower sludge production due to the digested part of microorganisms in this section. These two advantages make use of the system in the dairy industry. On the other hand, the bulking phenomenon due to

the lack of sedimentation creates excessive foam and toxic materials, meaning that projected and actual efficiencies of these systems are contingent on operator experience (84).

Table 4: Advantages and drawbacks of using different types of aerobic processes

Reactor type	Advantages	Disadvantages
ASP	• Easy to operate and install • Odor-free • Light footprint	• Low effluent quality • Higher sludge production • Energy-consuming operation • Bulking • Foam production • Precipitation of iron and carbonates • Decrease in efficiency during winter
Conventional or percolating filter	• High removal efficiency • Very efficient in the removal of ammonia • Appropriate for small- to medium-sized communities • Simple and reliable process	• Can be blocked by precipitated ferric hydroxide and carbonates • Not appropriate for the treatment of high-strength wastewaters
RBC	• High removal efficiency • Low power input needed • Easy to operate • Low maintenance • Less operator attention • Lower operating costs • Well-controlled against organic shocks • Low space requirement • Low sludge production • No risk of channeling	• Odor problems may occur • Needs permanent skilled technical operator for operation and maintenance purposes • Needs to be protected against sunlight, wind, and rain (especially against freezing in cold climates) • Considerable investment, operation, and maintenance costs • Contact media not available at the local market • Continuous electricity supply required (but uses less energy compared to trickling filters or ASPs in terms of comparable degradation rates)
SBR	• Easy to modify cycles • Small footprint • Cost-effective • Low flow applications • Wider wastewater strength variations • High removal efficiency • Capable of achieving nitrification, de-nitrification, and phosphorous removal • Wide operation flexibility • Minimal sludge bulking • Minor operation and maintenance issues • It May be operated remotely	• High energy consumption • Difficult to adjust cycle times for small communities • Frequent sludge disposal
MBR	• High effluent quality • High volumetric load possible • High rate of degradation • Lower sludge production • More compact • Energy saving • High removal efficiency	• Control of membrane fouling • Membrane fouling • Aeration limitations • Stress on sludge in external MBR • Membrane pollution • High cost

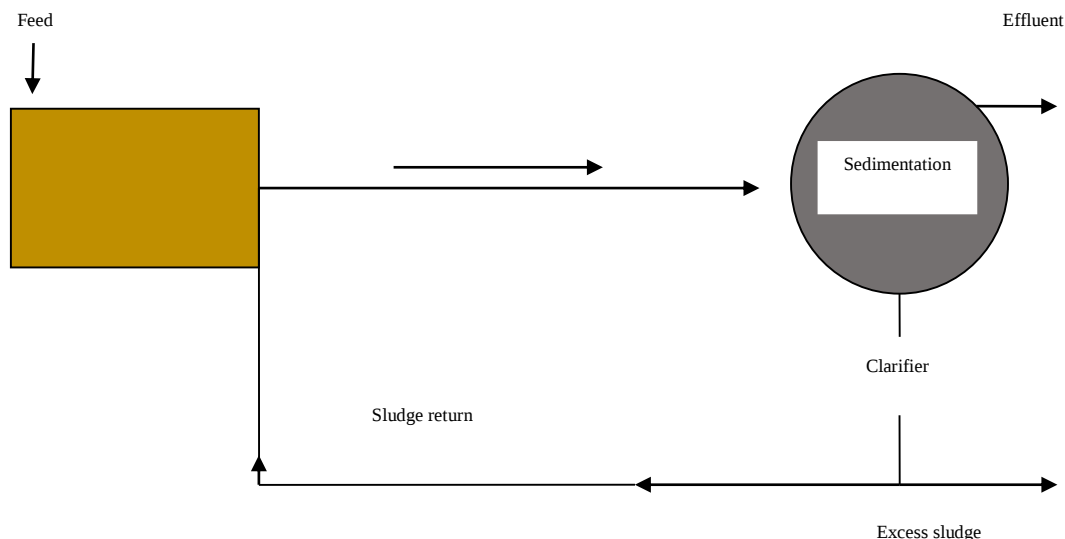


Fig. 4: Simplified illustration of activated sludge process for aerobic wastewater treatment system (102).

3.2.2 Conventional or percolating filter

Aerobic filters like typical trickling or percolating filters as shown in Fig. 5 are examples of the oldest biological treatment techniques that can produce high-quality effluents (102). The carrier media (20–100 mm diameter) may include pumice, rock, gravel, or plastic pieces, which are populated by a diverse microbial community. A storage tank wastewater is usually poured over the medium and then trickles via a medium with a 2 m bed. The sticky microbial film growing on the carrier medium absorbs the organic elements of the wastewater and absorbs compounds that will be decomposed aerobically in the film. Deposited sludge lyse needs to be removed periodically. The downward flow, as well as natural convection currents resulting from temperature differences between the air and added wastewater, contributes to facilitating aerobic conditions. The decomposition process might be improved by using forced ventilation, but the air must be deodorized in clarifying tanks to be used in this system. Typical filters with aerobic microbes growing on rock or gravel are restricted to

a depth of approximately 2 m because deeper filters improve anaerobic growth with subsequent odor issues. These having been said, filters with synthetic media can fully aerobic up to about 8 m (108). The final wastewater flows to sedimentation or clarifying tank to separate sludge and particles from the carrier medium. In general, organic loading for dairy wastewater must not be higher than 0.28–0.30 kg BOD/m³, and recirculation is required for this system (109). Kessler (110) presented a dairy effluent BOD removal of 92% and since the BOD of the final wastewater was still high, further treatment of effluent was performed in an oxidation pond to decrease the BOD content. An essential issue is that trickling filters can be clogged by deposited ferric hydroxide and carbonates, with the associated decrement of microbial activity. When overloading occurs with dairy wastewater, the medium will be clogged with heavy biological and fat films. Maris et al. (111) presented that biological filters are not suitable for treating high-strength wastewaters because filter blocking by organic precipitated on the filter medium is commonly found.

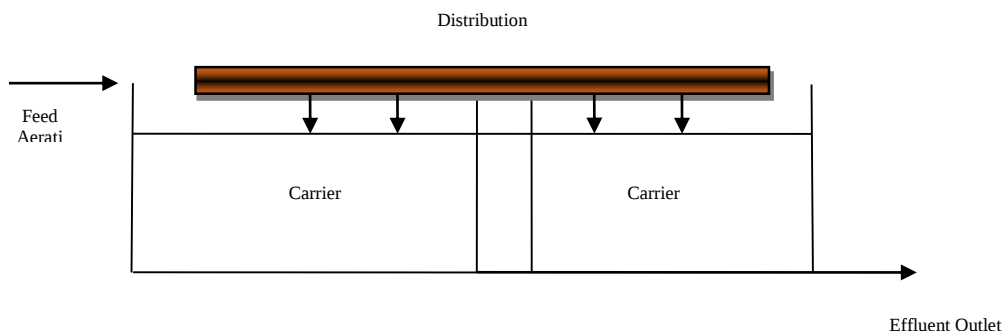


Fig. 5: Simplified illustration of aerobic filter for wastewater treatment processes (110)

3.2.3 Rotating biological contactors

The rotating biological contactor (RBC) design includes circular discs (Fig. 6) formed by high-density plastic or other lightweight materials (102). The discs that rotate at 1–3 rpm are located on a horizontal shaft such that 40%-60% of the disc surface stick out from the tank, making it possible for oxygen to transfer from the atmosphere to the exposed films. The oxidation of organic compounds of the effluent will be facilitated through developing a biofilm on the disc surface. The biofilm sludge will be torn off and removed from the sedimentation tank as soon as it becomes extremely thick. Operation efficiency is according to the g BOD per m² of disc surface per day (102). Rusten et al. (112) presented a COD removal efficiency of 85% with an organic loading rate (OLR) of 500 g COD/m³ hour when treating dairy effluent. The RBC process suggests various superiority over the ASP for employ in dairy effluent treatment. The major benefits of the RBC process are low power input needed, ease of operation, and low maintenance. Moreover, pumping, aeration, and wasting/recycling of solids are not necessary, thus reducing the required operator attention. In addition, the process of nitrogen separation is relatively easy, and only inspection and lubrication are involved in routine maintenance. The rotating discs mostly act as trickling filters; nevertheless, as compared to the trickling filter, RBC requires less land and lower operating costs. Another advantage of this system is the large amounts of microbial mass that can protect against organic shocks to the system.

3.2.4 Sequencing batch reactor

A sequencing batch reactor (SBR) is a single-tank fill-and-draw system (Fig. 7) that aerates, settles, withdraws effluents, and recycles solids (40, 102). The typical steps that

are carried out sequentially in SBR systems are: fill, react (aeration), settle (sedimentation/clarification), draw (the effluent is decanted), and idle. Wastewater is mixed without aeration process to provide metabolism of the fermentable components while the tank is filled. The following stage is the aeration process that contributes to the oxidation and biomass formation processes. Afterward, sludge is settled and the treated wastewater is separated to finalize the cycle. SBR depends strongly on the site operator to regulate the duration of each stage to reflect fluctuations in effluent composition (113). Owing to their nearly light footprint, SBRs are effective in locations where land is limited. It is likewise simple to improve cycles within the system for nutrient separation if required. In addition, SBRs are economical if treatment beyond the biological is necessary, like filtration. They also suggest potential capital savings by removing the need for clarifiers, are considered a reasonable choice for low flow applications, and allow for greater effluent strength alterations. SBRs need a high level of maintenance because of the timing units and controls. Based on the downstream processes, it may be required to equalize the wastewater after it exits the SBR. Eroglu et al. (53) and Samkutty et al. (114) proposed that SBR should be a practical primary and secondary treatment choice for treating dairy plant effluent with COD removals of 91% - 97%. Torrijos et al. (2001) (115) obtained the COD removal efficiency of 97% at a loading rate of 0.50 kg COD/m³ day using SBR in treating effluent from small cheese-making dairies. Meanwhile, Li and Zhang (116) efficiently operated an SBR at an HRT of 24 hours for treating dairy effluent with a COD content of 10 g/L and they achieved the removal efficiencies of 80% in COD, 63% in total solids, 66% in volatile solids, 75% in Kjeldahl nitrogen, and 38% in TN.

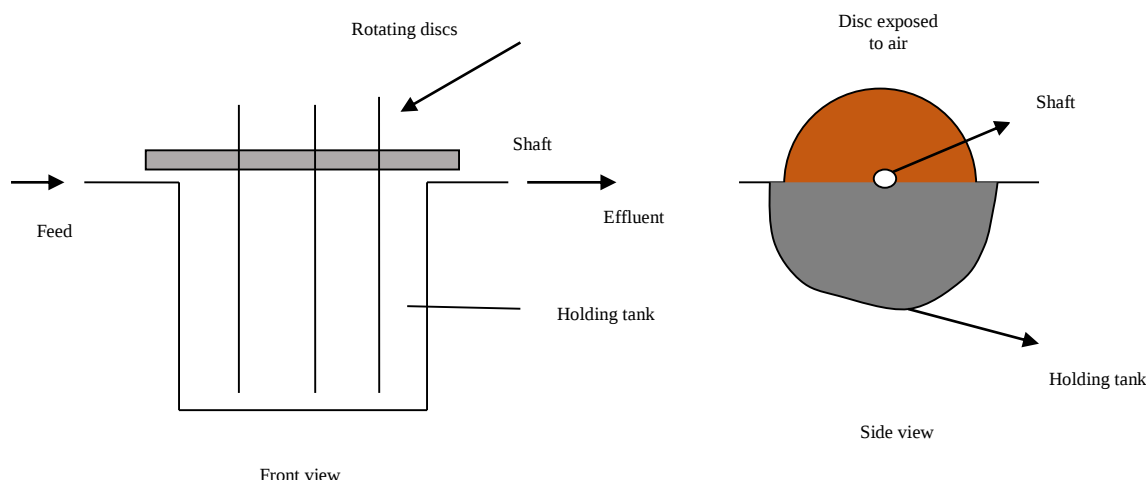


Fig. 6: Simplified illustration of aerobic effluent treatment processes: rotating biological contactor (112)

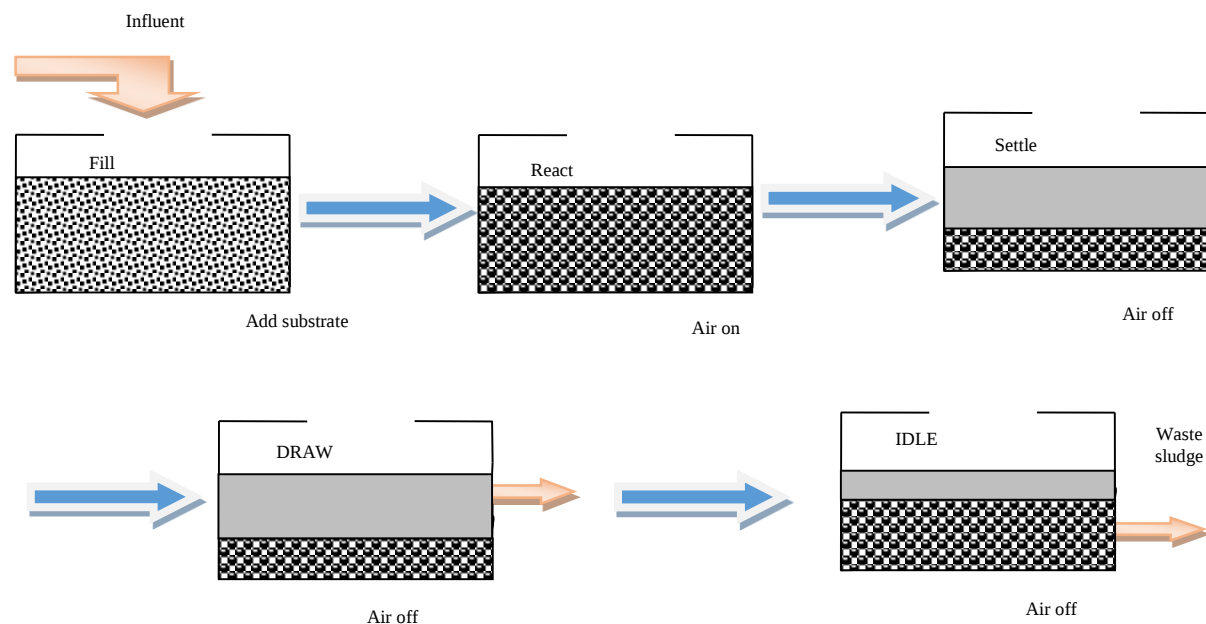


Fig. 7: Simplified illustration of aerobic wastewater treatment processes: sequencing batch reactor (102)

3.2.5 Membrane bioreactor

Recently, membrane bioreactors (MBRs), particularly submerged-type membranes (Fig. 8), have been gaining attention owing to their better-treated wastewater quality and lower sludge generation compared to typical ASPs (40, 117-119). In an MBR, membranes play a key role in solid/liquid separation. Two types of MBRs are different based on the placement of the membrane unit. Membranes are either submerged in the reactor or placed externally. The submerged membrane unit has attracted more attention recently since it is a compact system as well as uses low energy (117, 118, 120). One drawback of this system is that control of membrane fouling is more difficult compared to an external membrane system. Different techniques have been implemented, including the intermittent suction

method (121) and back flushing (122) to decrease membrane fouling. Similar to most membrane filtration systems, membrane fouling, as well as fouling control are the main issues for a cost-effective and feasible MBR system (123). In addition to MLSS, soluble microbial products are considered major membrane foulants (122). In testing the performance of MBR for dairy effluent treatment with an HRT of 36 hours and 0.13 kg COD/kg MLSS, a COD removal efficiency of 95% was observed. Increasing MLSS concentration in the MBR system did not considerably affect the removal efficiency of BOD₅ and COD. The concentrations of COD and BOD₅ used were 400 and 550 mg/L, and removal efficiencies achieved were 95% and 91% respectively.

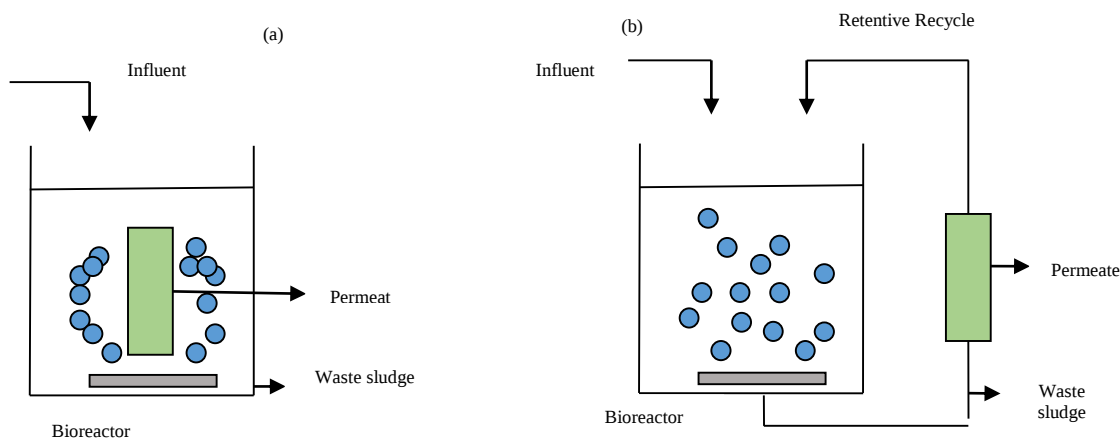


Fig. 8: The configuration of MBR system: (a) submerged MBR and (b) side-stream MBR configuration

3.2.6 Factors governing aerobic reactor choice

Aerobic granular activated sludge SBR (GAS-SBR) was recently proposed to provide a significant aerobic treatment rate as well as superior settling (40, 124). Schwarzenbeck et al. (32) presented 90% COD, 80% TN, and 67% TP removal efficiencies in a GAS SBR. While mixed culture AS is normally employed by scientists to treat dairy wastewater, bio-augmentation (adding external microorganisms with significant degradation capacity for specific wastewater) was successful at improving performance (125). Loperena et al. (126) demonstrated that, whereas commercial and mixed activated-sludge inocula presented similar rates of COD removal in batch experiments for treating dairy industrial wastewater, the COD degradation rate was higher for commercial inocula.

3.3 Major anaerobic biological treatment methods

Various anaerobic biological treatment techniques were developed to treat dairy products, including anaerobic digestion (AD), completely stirred tank reactor (CSTR), UASB, upflow anaerobic filter, anaerobic contact process, expanded bed and/or fluidized-bed digesters, fixed-bed digesters, and membrane anaerobic reactor system (MARS). Biological treatment methods are environmentally friendly for treating polluted air and also do not produce NO_x , SO_x , or secondary pollutants. Various factors, like pH, temperature, and gaseous retention time, have significant effects on biological processes and should be in optimum condition for obtaining high efficiency. The advantages and drawbacks of these methods are laid-out in Table 5.

An anaerobic filter is able to operate by individual-feeding such as upflow, downflow, and horizontal direction as well as multiple-feeding (40, 91, 127-129). The upflow anaerobic filter was widely applied for treating whey; it is able to operate efficiently for treating low and highly polluted dairy effluent at short HRT and high organic loading rate (130). Operating conditions and anaerobic filters treatment performances for treating dairy wastewater are presented in Table 6.

3.3.1 Anaerobic digestion

A biological process carried out via an active microbial community without presenting exogenous electron acceptors is known as anaerobic digestion (AD). In this process, up to 95% of the organic load in a waste stream can be turned into biogas (methane and carbon dioxide), while the rest is used for cell growth and maintenance (131). In general, anaerobic processes are rather efficient and cost-effective for the biological stabilization of dairy effluents because the high energy associated with aeration in aerobic systems is not required (59, 132). AD also produces methane, a source of heat and power (133). Furthermore, minor sludge is produced, diminishing problems associated with sludge removal. AD systems require nutrients such as nitrogen and phosphorus significantly lower than aerobic systems (108). Pathogenic organisms are generally destroyed, and the final sludge has a high soil conditioning content if the heavy

metals level is low. Dairy effluents treatment with high COD content without prior dilution, as required by aerobic processes, decreases the required space as well as related costs. Usually, there are no bad odors if the process is operated properly (134). High capital cost, long startup periods, rigorous control of operating conditions, and higher sensitivity to variable loads and organic shocks, in addition to toxic compositions are the drawbacks of anaerobic systems (135). Ammonia nitrogen is accordingly discharged with the digester effluent and generates oxygen demand in the receiving water since it is not separated in an anaerobic system. To obtain reasonable discharge standards, a complementary treatment is also necessary. As demonstrated in previous works, a remarkable disadvantage of aerobic treatment plants is the high energy demands. COD contents of dairy wastewater change considerably; furthermore, dairy wastewaters are warm and highly polluted, making them ideal for anaerobic treatment (135). Furthermore, no aeration is required, the level of sludge production is low, and the area demand is low.

3.3.2 Completely stirred tank reactor

One of the simplest types of anaerobic digester is a completely stirred tank reactor (CSTR) (136, 137). Sahm (138) stated that the OLR rate ranges from 1 kg to 4 kg organic dry matter $\text{m}^3 \text{day}^{-1}$, and the digesters generally have capacities of 500 to 700 m^3 . CSTRs reactors are usually employed for concentrated effluents, particularly those whose polluting matter is mostly SS and has COD values greater than 30,000 mg/L. There is no biomass retention in this reactor; as a result, the HRT and sludge retention time (SRT) are not separated, necessitating long retention times that depend on the growth rate of the slowest-growing bacteria in the process of digestion. Ross (139) reported that the HRT of the typical digesters is similar to SRT, which can vary from 15 to 20 days. This type of digester was employed by Lebrato et al. (140) for treating effluent of the cheese factory. Although 90% COD separation was obtained, the digester could only work at a minimum HRT of 9.0 days, which was likely because of biomass washout. The effluent, containing 80% washing water and 20% whey, had a COD of 17,000 mg/L. This type of reactor is very beneficial for laboratory-scale studies, but it is hardly a feasible choice for industrial-scale treatment because of its HRT limitation.

3.3.3 Upflow anaerobic sludge blanket

Lettinga et al. (1991) (141) designed a UASB reactor for commercial applications. A schematic diagram of this reactor is shown in Figure 9. UASB reactor was used for treating maize-starch effluents in South Africa for the first time (142), however, the full potential of the UASB reactor was only discovered after a significant development program by Lettinga in the late 1970s (141, 143). The UASB has only recently been used in anaerobic treatment. Through UASB, pollutants in wastewater are degraded by microbes that produce 75%-80% CH_4 by volume, 15%-25% CO_2 , and minor amounts of N_2 , H_2 , and other gases.

Table 5: Advantages and drawbacks of using different forms of anaerobic processes

Reactor type	Advantages	Disadvantages
AD	• Low energy requirements • Less sludge is generated • Methane production, which can be utilized as a heat or power source • Fewer requirements to N and P • Lack of pathogenic organisms • Fewer space requirements • Cost-effective • High removal efficiency	• High capital cost • Long startup periods • The strict control of operating conditions • Greater sensitivity to variables loads and organic shocks • Toxic compounds • High energy requirements
CSTR	• No biomass retention • High removal efficiency • Continuous operation • Reasonable temperature control • Simply adapts to two-phase runs • Reasonable control • Ease of operation • Minor operating (labor) cost • Easy to clean	• Very low conversion per unit volume • By-passing and channeling probably with weak agitation performance
UASB	• High removal efficiencies • No support material is required • Cost-effective • Great decrement in organics • Can tolerate high OLRs (up to 10 kg BOD/m³/d) and hydraulic loading rates • Minor sludge generation (and thus, infrequent deluging required) • Biogas can be applied for energy (but generally needs scrubbing first)	• Long start-up period • Sufficient amount of granular seed sludge • Reactor needs a skilled operation
Upflow anaerobic filter	• High OLRs • Short HRT • High removal efficiency • Stable against organic and hydraulic shock loading • No electrical energy is needed • Minor sludge production; the sludge is stabilized	• Requires expert design and construction • Low reduction of pathogens and nutrients • Effluent and sludge require further treatment and/or proper discharge • Risk of clogging, depending on pre- and primary treatment • Removing and cleaning the clogged filter media is difficult
MARS	• Enhances biomass retention • High removal efficiency	• High retention time
Fixed-bed digester	• High removal efficiency	• Saturated region • Difficult to design accurately
Expanded bed and/or fluidized-bed digesters	• High removal efficiencies • Can control and optimize the biological film thickness • Elimination of bed clogging • Low hydraulic head	• Problems of channeling • Plugging • Gas hold-up
Fixed-bed digester	• Greater surface area • Capital cost is lower	
Anaerobic contact process	• Poor settling properties • High removal efficiencies • Varies temperature ranges • No oxygen requirements • Ethane is a useful end product	• High retention time • Poor settling properties

Table 6: Operating conditions and anaerobic filter performances for dairy effluent treatment (40).

Feed type	Wastewater	Packing media	Temp. (°C)	pH	HRT (d)	OLR (kg COD m ⁻³ d ⁻¹)	Influent COD (g L ⁻¹)	COD Removal (%)	CH ₄ yield (m ³ CH ₄ kg ⁻¹ COD)	Reference
Up-flow	Whey	Polyethylene/clay	37	7	10-15	2.2-3.3	33	90	—	(144)
Up-flow	Whey	Flocor	35	5.7-7.5	1-5	1-4	5-20	72-90.2	0.089-0.28	(97)
Up-flow	Dairy	Polypropylene	32-34	6.8-7.2	0.83-12.5	0.5-6.5	2-6	>80	0.32-0.34	(95)
Up-flow	Synthetic dairy	PVC rings	35	—	2	1.44-6.29	3-12	97.9-98.8	0.32-0.39	(145)
Down-flow	Simulated whey	Polyethylene	35	5.9-7.8	5	2.6	13	66-93.6	0.236-0.26	(146)
Horizontal-flow	Synthetic whey	Ceramic	40	6.9	1	1-10.2	1-10.2	85-93.8	0.158-0.35	(147)

Methane gas contains a high calorific level; thus, by utilizing this type of reactor, the produced methane is separated and used as an alternative energy source. This system, therefore, is feasible and efficient for the waste contains a high level of BOD. The rather simple design of the UASB digester (Fig. 9) is according to the premier settling properties of granular sludge. The granules' growth and development are keys to the success of the UASB reactor. Note that the presence of granules in the UASB digester eventually contributes to removing the HRT from the SRT. Therefore, efficient granulation is necessary to achieve a short HRT without inducing biomass washout. The effluent is fed from the bottom and exits at the top through an internal baffle system to separate the gas, sludge, and liquid phases. The granular sludge and biogas are separated using this device. A COD loading of 30 kg/m³ day can be treated with a COD separation efficiency of 85%–95% at optimal conditions. The methane level of the produced biogas ranges from 80% to 90% (v/v). HRTs of as low as 4 hours are practical, with superior settling sludge and SRT of greater than 100 days. The UASB is highly economical because it uses less pump energy for the recirculation of effluent and does not require other expenses. The UASB system greatly relies on its granulation process with particular organic wastewater in comparison with other anaerobic technologies. Removal efficiencies of 95%–99% can be obtained by employing the UASB. The main point of the UASB system is that it does not need support material for retaining high-density anaerobic sludge. But, the absence of carriers makes the availability and maintenance of biomass that settles easily, either as flocs or as dense granules (0.5–2.5 mm in size) necessary. In order to separate biogas and bacterial mass which are returned into the active lower zone of the reactor on the other side, a three-phase separator (biogas, liquid, and biomass) is required.

In 1991, UASB reactor performance was evaluated in the anaerobic wastewater treatment of cheese. The

percentages of COD with an organic loading rate of 31 g/L/D of COD were 90 percent (148). An anaerobic upflow filter was used in a 2008 study on the treatment of whey. In 2008, a UASB system was used to evaluate the removal efficiency of whey. With a concentration of 5000 mg/L and an HRT variety of 1 to 4 days, the removal efficiency was increased dramatically from 70% to 90% (6). Performance evaluation of the dairy wastewater treatment using UASB reactors under various experimental conditions and at various scales is summarized in Table 7. As shown in this Table, COD removal from dairy wastewaters in UASB reactors changes from 50% to 98%.

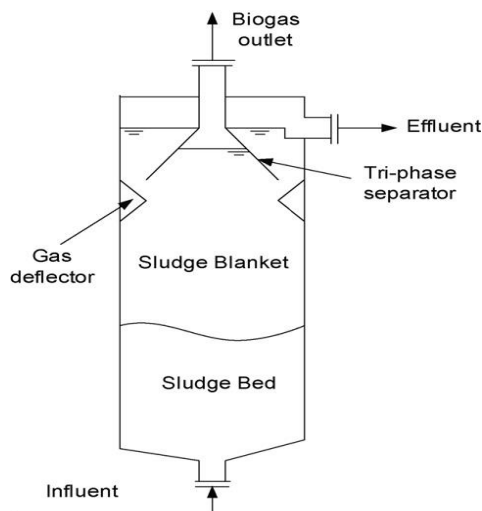


Fig. 9: Schematic diagram of a UASB system (48, 149). (Reprinted from Biological Wastewater Treatment in Warm Climate Regions, p. 723, ISBN 9781843390022 with permission from the copyright holders, IWA).

Table 7: Results of the UASB reactors performance for the dairy wastewater treatment (150)

Reactor volume (L)	COD IN (mg/L)	COD removal (%)	Reference
–	1440	53-91.5	(151)
31.7	700-1200	50-93	(152)
6	–	96-98	(6)
1.8	1500-2000	90	(153)
10/2	4056	79.4/85.5	(154)
6	101-541	98	(155)
5	2038-4728	69	(156)
120,120	1250-2250	78.78-87.06	(157)
14	800-4080	64	(158)
4.32	5240	78	(159)
48,000	20,314	88.23	(160)
120	1000-2000	95	(161)
6.6	500-3300	67	(162)

3.3.4 Upflow anaerobic filter

Young and McCarty developed the upflow anaerobic filter in 1969 (163). Its mechanism is like the aerobic trickling filter mechanism. The upflow anaerobic filter is loaded with inert support material, like gravel, rocks, coke, or plastic media; therefore, the system does not require biomass removal or sludge recycling. The AFR can function as a downflow or an upflow filter reactor with an OLR ranging from 1 kg/m³ to 15 kg/m³ day COD and COD separation efficiencies of 75%–95%. The treatment temperature is between 20 °C and 35 °C with HRTs ranging from 0.2 to 3 days. The potential risk of clogging via undegraded SS, mineral precipitates, or bacterial biomass is the major disadvantage of the upflow anaerobic filter. Their usage is also limited to effluents with COD ranging from 1000 to 10,000 mg/L (139). Bonastre and Paris (164) reported 51 anaerobic filter applications, of which 5 were applied for pilot plants and 3 were used for industrial-scale dairy effluent treatment. The anaerobic filters were worked at HRTs ranging from 12 to 48 hours, while COD separation ranged from 60% to 98%. The organic loading rate changed from 1.7 to 20.0 kg COD/m³ day.

Separated phase digesters are developed to spatially remove acid-forming bacteria and acid-consuming bacteria. Separated phase digesters are beneficial for treating effluents either with unbalanced ratios of carbon to nitrogen (C:N), like effluents with high protein concentrations, or effluents that acidify quickly, like dairy effluents (165). The main points of these digesters are high OLRs and short HRTs. Burgess (166) presented two cases where dairy effluents were treated applying a separated phase industrial-scale process. One dairy had an effluent with a COD content of 50,000 mg/L and a pH value of 4.5. Two phases of digester were worked at 35°C. The acidogenic reactor functioned at an HRT of 24 hours, and the methanogenic reactor was operated at an HRT of 3.3 days. 50% of the COD was transformed to organic acids in the acidification tank, while only 12% of the COD was separated. The OLR for the acidification and methane reactors were 50.0 kg COD/m³ day and 9.0 kg COD/m³ day respectively. A total COD decrement of 72% was obtained. The methane content in biogas was 62% and the supplied data showed that a methane yield (YCH₄/COD removed) of 0.327 m³/kg COD removed was achieved.

3.3.5 Membrane anaerobic reactor system

The digester effluent is filtered via a filtration membrane in a membrane anaerobic reactor system (MARS). Li and Corrado (167) investigated the MARS (well-mixed digester with an operating volume of 37,850 L integrated with a microfiltration membrane process) on cheese whey including up to 62,000 mg/L of COD. The digester effluent was filtrated by the membrane and permeate was released. The retentate, which contained biomass and SS, was recycled to the digester. The COD separation efficiency was 99.5% at an HRT of 7.5 days. The most important achievement of the study was that the process control parameters attained in the pilot plant could adequately be employed in their industrial-scale plant. The anaerobic digestion ultrafiltration system (ADUF) similar to the membrane system has successfully been employed in lab-scale and pilot-scale investigations of dairy wastewaters (168). The ADUF process does not employ microfiltration, but rather an ultrafiltration membrane. Therefore, far better biomass retention efficiency is achievable with the ADUF. Prieto et al. (169) developed a composite bioactive membrane for wastewater treatment and used it to produce and capture hydrogen (H₂) which is a source of energy.

3.3.6 Fixed-bed digester

The fixed-bed digester (Fig. 10) includes permanent porous carrier materials. Through extracellular polysaccharides, bacteria are able to attach to the surface of the packing material and still stay in tight contact with the passing effluent. The wastewater is fed either at the bottom or at the top to make upflow or downflow arrangements, (170) employing a downflow fixed-film digester for treating deproteinized cheese whey with an average COD of 59,000 mg/L. The digester obtained a COD decrement of 90%–95% at an HRT and OLR of 2.0–2.5 days and 12.5 kg COD/m³ day respectively. The deproteinized cheese whey had a mean pH of 2.9 although the digester pH was frequently above 7.0 (171). De Haast et al. (172) employed a bench-scale fixed-bed digester including an inert polyethylene bacterial carrier for treating cheese whey. They achieved the best results at an HRT of 3.5 days, with 85%–87% COD separation. The organic loading rate was 3.8 kg COD/m³ day, and biogas yield amounted to 0.42 m³/kg COD added per day. The

biogas contained a methane level of between 55% and 60%, and 63.7% of the calorific value of the substrate was conserved in the methane.

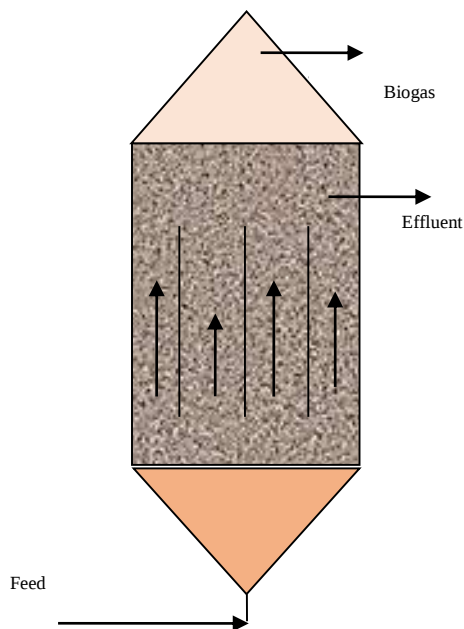


Fig. 10: A simplified illustration of anaerobic wastewater treatment processes: fixed-bed digester.

3.3.7 Expanded bed and/or fluidized-bed digesters

In comparison with the fixed-bed reactor, an anaerobic fluidized bed reactor has superior mass and heat transfer characteristics. Furthermore, it has a great level of attached biomass, which is rich in microbial diversity. It becomes stable quickly after changing operational conditions (40, 173, 174). Operating conditions and evaluation of anaerobic fluidized bed reactors for treating dairy industry wastewater are summarized in Table 8. As shown in Fig. 11, in fluidized bed digesters, effluents pass upwards via a bed of suspended media to which bacteria attach (175). The carrier medium continuously remains in suspension through strong, efficient liquid phase recirculation. The carrier media consist of plastic granules, sand particles, glass beads, clay particles, as well as activated charcoal fragments. Parameters that contribute to having an efficient fluidization system for this process are (a) utmost contact between the liquid and the fine particles carrying the bacteria; (b) avoiding issues of channeling, plugging, and gas hold-up, generally occurring in packed beds; and (c) the ability to control and optimize the thickness of the biological film (138). Toldra et al. (176) applied this process for treating dairy effluent with a COD of only 200–500 mg/L at an HRT of 8.0 hours and a COD separation of 80%. Note that with the fundamental changes found between different types of dairy wastewater, this specific dairy wastewater seems to be at the bottom end of

the scale in terms of its COD content and organic load. The dairy effluent was apparently generated by a dairy with very good product-loss control and a relatively great level of water use (165).

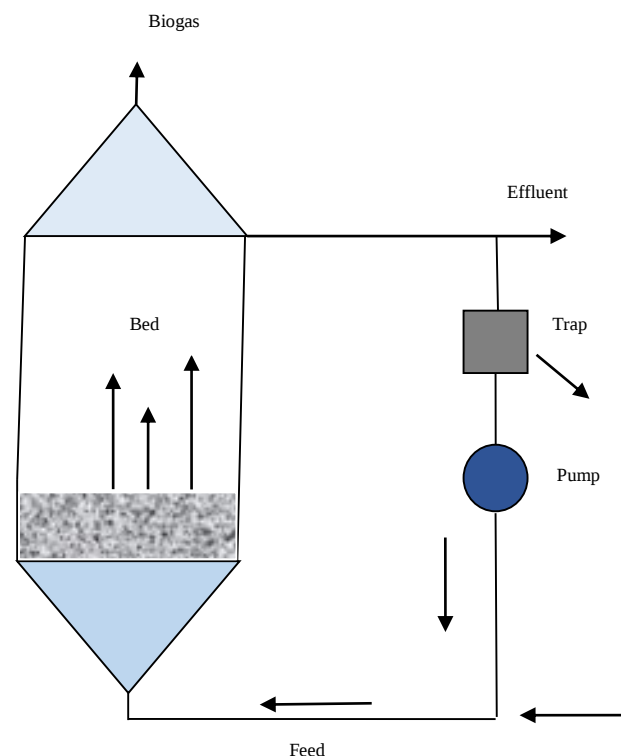


Fig. 11: A simplified illustration of anaerobic effluent treatment processes: fluidized-bed digester.

3.3.8 Anaerobic contact process

The anaerobic contact system (Fig. 12) was built in 1955 (177). This system is basically an anaerobic ASP that comprises a well-mixed anaerobic reactor followed by a model of biomass separator. The removed biomass is returned to the reactor, therefore decreasing the retention time from the typical 20–30 days to 10 days. Given that the bacteria are maintained and recycled, this model of the plant would be capable of treating medium-strength effluent (200–20,000 mg/L COD) very effectively at great organic loading rates (138). The organic loading rate can change between 1 kg/m³.day and 6 kg/m³.day COD with COD separation efficiencies of 80%–95%. The treatment temperature varies between 30°C and 40°C. The main drawback of this process is the poor settling properties of the anaerobic biomass from the digester effluent. Dissolved air (178) and biogas floatations methods (179) were used as alternative sludge removal methods in this system. Although the contact digester is assumed to be obsolete, numerous dairies throughout the world still use this system (180).

Table 8: Anaerobic fluidized bed reactors performances at different operating conditions for dairy effluent treatment (40)

Feed type	Wastewater	Packing media	Temp. (°C)	pH	HRT (d)	OLR (kg COD m ⁻³ d ⁻¹)	Influent COD (g L ⁻¹)	COD Removal (%)	CH ₄ yield (m ³ CH ₄ kg ⁻¹ COD)	Reference
Up-flow	Ice-cream	Saponite	35	6.8-7.2	0.25-0.50	3.2-23.4	5.2-11.7	94.4	–	(90)
Up-flow	Simulated milk	Selfimmobilized granules	37	–	0.75-5	2.22-31	10-77.5	78	0.27	(181)
Up-flow	Dairy	Sand	20, 35	–	0.08-0.33	0-12	0.2-0.5	80	–	(182)
Up-flow	Ice-cream	Sand	35	–	1	1-12	5	70-90	0.157-0.193	(183)
Down-flow	Dairy	Polystyrene balls	–	6.8-7.4	7.5-11.3	10	3.2	85-98	0.37	(184)
Down-flow	Synthetic dairy	Silica and aluminum	37	–	12-72	1.33-8	4	40-80	–	(185)
Down-flow	Synthetic dairy	Granular silica	35	–	3-60	0.5-10.1	30	75-98	–	(186)
Down-flow	Synthetic dairy	Granular silica	35	–	2.5-60	0.5-12.2	30	90-96	–	(186)

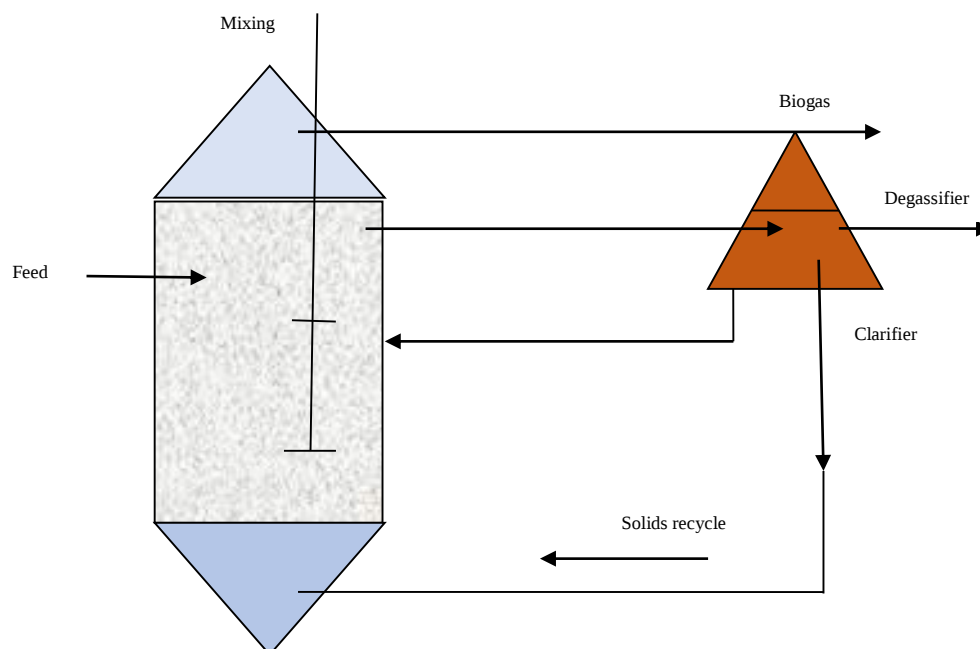


Fig. 12: A simplified illustration of anaerobic effluent treatment processes (Contact digester).

3.3.9 Factors influencing the choice of anaerobic reactor

Compared to the established technologies in the market, industries prefer a better and more dependable technology that would need minimal land area and capital. In terms of an AD system, a process capable of running at high loading rates of organic and hydraulic fits the technology criteria. Ideally, this process requires minimal maintenance and operation. In order to determine an ideal reactor type for a certain application, a systematic evaluation must be conducted on several configurations between the reactor and the wastewater stream. Notably, three factors influence the organic and hydraulic loading potential of a reactor, namely (i) the amount of active biomass per unit volume that can be retained by a reactor, (ii) contact opportunity between the retained biomass and the incoming wastewater, and (iii) diffusion of the substrate within the biomass.

Considering the determinants, the most prominent option is the granular sludge UASB reactor. Prominently, the only constraints that the reactor has are its granules' propensity to float at high loading rates [the granules tend to shear]. To a smaller extent, these limitations also apply to attached biomass reactors such as fluidized beds, fixed-film, and rotary biological contactors. The media occupy the space, causing the attached biomass reactors to have a relatively lower capacity for biomass retention of the reactor per unit volume. This capacity is determined by the film thickness whilst the fluidized bed reactor has the highest rate because it has a large surface area for the attachment of the biomass. Furthermore, the fluidized bed and expanded granular sludge bed (EGSB) systems demonstrate further contact between the retained biomass and the incoming wastewater. Nevertheless, the diffusion of the substrate within the biomass in these configurations is restricted because of the high upflow velocity.

Factoring all of the findings, the maximum loading rates that may be achieved with soluble wastewater are highest in UASB, followed by EGSB, fluidized bed reactor, and anaerobic filter. Accordingly, Rajeshwari et al. (187) held the same order in terms of the requirements of land area and the capital cost of the reactors. Moreover, only minimum maintenance and digester operation is required, provided that the process is adequately stable against the changes in conditions of the environment and fluctuations in the wastewater characteristics. The potential utilization of a reactor determines the susceptibility of the process and, consequently, a system that operates at loading conditions near the maximum level has higher sensitivity as compared to the other systems. Table 9 outlines the recommendations in choosing a reactor based on the comparison of numerous types of reactors (187).

3.4 Major combined biological treatment methods

Depending on the type of pollution and based on biological treatment methods, wastewater treatment systems are categorized into aerobic, anaerobic, and combination methods. As mentioned above, dairy industrial wastewater with a high organic concentration always encounters significant complications. Thus, aerobic and anaerobic methods cannot sufficiently remove all low- and high-loading combinations. As a result, combining two methods or multi-stage methods can compensate for the weaknesses of each individual method and improve the performance of processes (188). Recently, combined anaerobic reactors have been widely used for the treatment of dairy wastewater and performance evaluation and operating conditions of these reactors are listed in Table 10.

Table 9: Recommended factors to choose anaerobic reactors.

Factors	Grade order
Operational competence	Fixed film < UASB < RBC < fluidized bed
Energy usage	UASB < fixed film < EGSB < fluidized bed < RBC
Capital cost, land area demand, operation and maintenance	RBC < fixed film < UASB < EGSB < fluidized bed

Table 10: Anaerobic integrated reactors performances at different operating conditions for dairy effluent treatment (40).

Reactor type	Wastewater	Packing media	Temp. (°C)	pH	HRT (d)	OLR (kg COD m ⁻³ d ⁻¹)	Influent COD (g L ⁻¹)	COD Removal (%)	CH ₄ yield (m ³ CH ₄ kg ⁻¹ COD)	Reference
Hybrid	Synthetic dairy	Polyethylene	35, 55	–	0.5, 1	1, 2	1	64–76	0.03–0.24	(189)
Biofilm supported CSTB	Synthetic dairy	Low-density nylon meshes	Room temperature	6.5–6.8	10	–	–	46–59	–	(190)
Downflow-upflow hybrid	Whey	Polyethylene	–	7.5	–	0–14	55–70	90–98.4	–	(173)
Hybrid UASB	Dairy	Polyurethane foam	30	–	1	–	1	80.1–90.3	–	(191)
Bio-nest reactor	Dairy	Plastic ring	25–30	–	0.42–1	1.93–5.0	–	–	–	(192)
Hybrid UAS	Dairy	Plastic cut rings	–	5.9–7.6	0.25	8–20	5	65–93	0.25–0.31	(96)
Hybrid UAS	Dairy	–	35	–	1.9	0.97–2.82	1.9–5.34	91–97	0.27–0.359	(59)

3.4.1 Anaerobic RBC and aerobic SBR systems

In an RBC system, microorganisms form a biological film and attach it to an inert support medium that has a sequential disc configuration. The support medium is submerged partly or totally; it also gradually rotates around a horizontal axis in a tank with flowing wastewater. Fig. 13

illustrates a diagram of an anaerobic RBC system. Both anaerobic and aerobic RBC reactors have a similar configuration except a covered tank in the former, which prevents contact with air (193). Notably, the sole application of anaerobic RBC in the treatment of highly polluted synthetic wastewater yields a final COD of the RBC effluent

that is still deemed as excessively high. The initial COD concentrations of the synthetic wastewater were between 3248 and 12,150 mg/L. Despite achieving satisfactory efficiencies of overall COD removal at an HRT of 32 h (ranging from 74 % to 82 %), it is necessary to perform more treatment (194).

The RBC system has several advantages: (i) short retention time, (ii) low energy requirements, (iii) low operating costs, (iv) excellent process control, and (v) ability to handle an extensive range of flows. On the contrary, the main disadvantage of the system is its susceptibility to wastewater characteristics. This causes restricted operational flexibility to different operating and loading conditions. Apart from these, frequent maintenance is also required on its mechanical drive units and shaft bearings. Furthermore, the fill- and draw-AS systems have an improved version, the aerobic SBR, which is comprised of one or more tanks. Each tank has the capability to perform solid separation and waste stabilization. Kim et al. (195) explained the advantages of the SBR process: (i) flexibility in the treatment of variable flows, (ii) providing options for aerobic or anaerobic conditions in the same tank, (iii) minimum operator interaction, (iv) efficient oxygen contact with microorganisms and substrates, (v) good removal efficiency, and (vi) small floor space. Due to these benefits, the process has been implemented at an increasing rate in industrial (196-198) and municipal (199) wastewater treatment.

A combination of the anaerobic RBC and aerobic SBR systems will lead to efficient bioenergy production and waste treatment system as high methane production rates can be achieved via anaerobic RBC, and diluted waste can be treated efficiently via the aerobic SBR. To that end, integration of anaerobic RBC and three aerobic SBRs was adopted in the treatment of screened dairy manure and also in the treatment of a mixture of cheese whey and dairy manure. In general, this combination system is able to attain a significant reduction in COD (a minimum of 98%) and generate a considerable amount of methane gas.

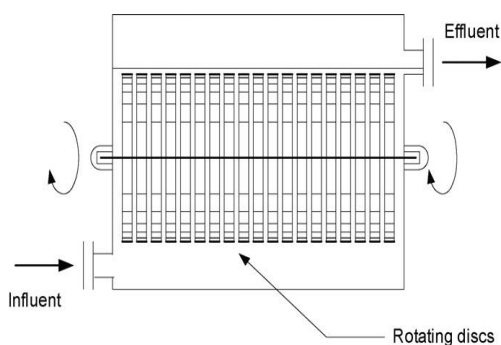


Fig. 13: Simplified diagram of an anaerobic RBC reactor (149).
(Reprinted from Biological Wastewater Treatment in Warm Climate Regions, p. 719, ISBN 9781843390022 with permission from the copyright holders, IWA).

3.4.2 UASB and aerobic fluidized bed system

Mobile supports to fill the fluidized bed reactors; hence, the particles covered with biofilm are fluidized through the liquid recirculation. Consequently, the constraint of substrate diffusion which is common in the stationary bed process is eliminated. Fig. 14 depicts a graph of an aerobic fluidized bed (AFB) system. Heijnen et al. (200) and Shieh and Keenan (1986) (201) outlined the advantages of the AFB reactor: (i) high biomass concentration, (ii) short HRT, (iii) high organic loading rate, (iv) small external mass transfer resistance, (v) large surface area for mass transfer, and (vi) no bed clogging. Contrary to this, Lazarova and Manem (202) and Saravanane and Murthy (203) stated that the system's applicability on a large industrial scale would be hampered by many issues, namely the control of the biofilm's thickness, oxygen distribution system, and bed expansion. In addition, the system also records elevated energy consumption as it operates on an exceedingly high ratio of liquid circulation.

Typically, there are three phases in the general mode of operation for an AFB reactor in the treatment of wastewater: (1) the discrete solid phase of inert particles with immobilized microbial cells, (2) the discrete air bubbles, and (3) the continuous aqueous solution. Research by Tavares et al. (1995) showed that the AFB process with the three phases resulted in the attainment of a high percentage (82%) in the average COD removal efficiency during synthetic wastewater treatment. It is to be noted that, the initial feed content was 180 mg/L and the process was performed at a low average HRT of 30 min. With this result, the reactor showed its potential in treating lowly polluted wastewater that has a COD content of 100 mg/L to 200 mg/L (204). Furthermore, research by Yu et al. (65) on the treatment of synthetic textile medium-polluted wastewater with a COD content of 2700 mg/L obtained a total of 75% COD removal efficiency. This result was achieved by combining UASB with the AFB reactor at an overall HRT of 14 h. Compared to the aerobic system, the combination of UASB and AFB generated a 45% lower sludge volume. Nonetheless, the anaerobic biomass (~1 g volatile solid [VS]/L) incorporated into the AFB reactor to improve the removal of COD led to an increasing level of suspended solids (SS). This is because the anaerobic biomass deactivates at a fast rate under aerobic conditions; consequently, the particular activity of aerobes is diluted by the dead anaerobic cells.

To that end, minimal cell mass from the UASB reactor has to be ensured before the process in the AFB reactor. This is to circumvent the anaerobes from having biological activity with high turbidity that does not have any contribution. The biological treatment of industrial wastewater of medium level of pollution may apply to the UASB-AFB system due to its reduced sludge formation, high pH tolerance, and stable performance in the removal of COD. The UASB-AFB system is also ideal in economic, technical, and environmental terms, particularly when space is a constraint.

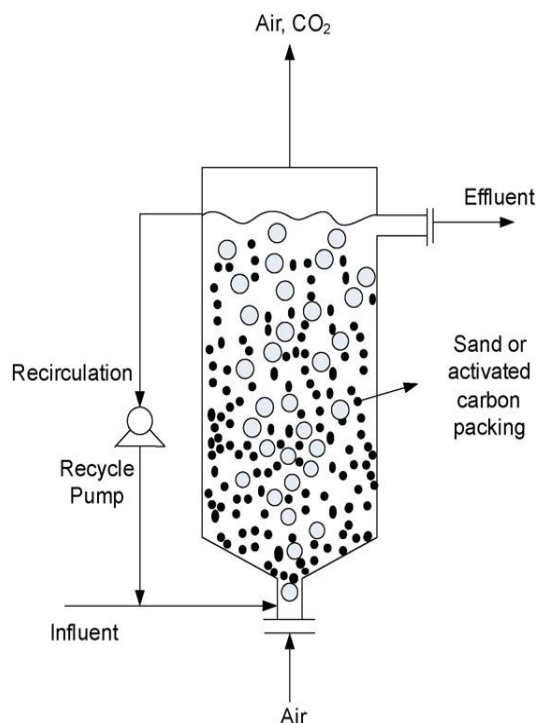


Fig. 14: Schematic diagram of an AFB reactor (149). (Modified from Biological Wastewater Treatment in Warm Climate Regions, p. 717, ISBN 9781843390022 with permission from the copyright holders, IWA).

3.4.3 Anaerobic–aerobic fixed-film bioreactor system

Compared to suspension culture, the immobilized cells on the surface of the media, or fixed film, are superior because they (i) have a wider variation in the population, (ii) have a higher rate(s) of growth, (iii) demonstrate faster utilization of the substrate concerning free biomass, and (iv) are less sensitive to the variations in environment in terms of pH, temperature, and toxic substances. Bishop (205) stated that the fixed cells endure physiological modifications because of the increasing local concentration of enzymes and nutrients or the extracellular polymeric matrix, which have a selective effect on toxic or inhibitory substances. Consequently, these cells exhibit the outlined advantages. Apart from that, Del Pozo and Diez (206) examined a combination of two FFBs – anaerobic and aerobic – with arranged media, linked serially with recirculation for the treatment of wastewater from a poultry slaughterhouse. The implementation of FFB in the slaughterhouse wastewater was done due to the severe problems of flotation in the suspended biomass systems, which were caused by the substantial levels of grease and oil. Clogging was avoided by placing the long corrugated PVC tubes as the support media vertically. Moreover, the tubes have a rough structure that attributed to the increase in the specific surface and acted as a protection from stress forces for the biomass attached. As a result, the overall COD removal efficiency of 92% was attained at an organic loading rate of 0.39 kg/m³.day. Fig. 15 depicts the illustration of the anaerobic-aerobic FFB.

These having been said, analysis of the fraction of COD removed by every reactor was done by evaluating the effects

of recirculation ratio (R/F) and anaerobic/aerobic volume ratio (Van:Vae). Accordingly, the downflow manner was applied for the FFBs, and recirculation of the aerobic effluent was done on the anaerobic FFB. Consequently, the removal of COD was prominently evident in the anaerobic FFB. Furthermore, this effect was inflated with an increase in the contribution of denitrification, namely as the R/F increased from 1 to 6. Apart from that, a smaller volume of aerobic FFB compared to the anaerobic FFB also led to an increase in the fraction of COD removed in the anaerobic FFB. This is explained by the large recirculation in the anaerobic FFB feed that favoured denitrification as opposed to the detriment of the methanogenic process and the generation of biogas.

3.4.4 Anaerobic upflow bed filter and aerobic membrane bioreactor system

An anaerobic hybrid reactor, the anaerobic upflow bed filter (UBF) is a combination of an anaerobic FFB and a UASB. UASB is installed at the lower part of the UBF reactor which develops the granular sludge. Conversely, FFB is found at the upper part of the UBF with the support of stationary packing material. Notably, the problems of clogging and biomass washout occur regularly in both anaerobic FFBs and UASBs; UBF is capable of eliminating these problems. In aerobic MBRs, membrane filtration is merged with biodegradation processes and sieving enables the occurrence of solid-liquid separation. MBR retains solid materials, pathogenic bacteria, biomass, and macromolecules while simultaneously tolerating smaller solution species and water to permeate the membrane (207, 208). Consequently, the process ensures the production of high-quality effluent. Dhauadi and Marrot (209), Muller et al. (210), and Wang and Wu (211) listed several advantages that MBR has: (i) separation of solid retention time (SRT) from HRT, (ii) high-quality effluent, (iii) reduced production of sludge due to the endogenous respiration during the long SRT and (iv) low rate of sludge-loading. Normally, the membrane-retained aqueous and particulate-based enzymes disappear in the conventional step of sedimentation clarification. This situation is different in MBR, and hence, the metabolic rate with this process would be improved (212). On the contrary, membrane fouling is a major disadvantage in the adoption of MBR. Generally, this issue is addressed by applying cross-flow filtration. A study by Ahn et al. (213) investigated the treatment of highly polluted wastewater with a COD content range of 6000 mg/L to 14,500 mg/L. The anaerobic UBF-aerobic MBR system was implemented at a relatively short HRT (24 h) and the results showed significant removal of COD at 99%. Fig. 16 illustrates a diagram of this system. Apart from that, and despite the superiority of the system, membrane fouling was still evident. Compared to a unit MBR that was run under similar settings, the trans-membrane pressure was approximately nine times higher. The increased extracellular polymeric substance and hydrophobicity led to serious fouling in the system. In addition, the membrane-coupled ASP is a representative of the MBR system. It merges the AS system with membranes and performs specifically efficiently in organic matter removal as an advanced secondary wastewater treatment process.

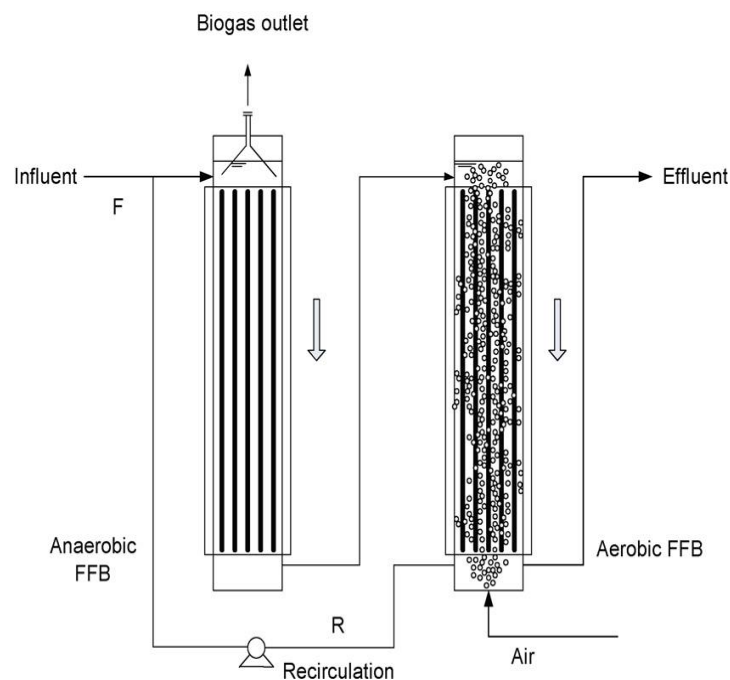


Fig. 15: Schematic diagram of anaerobic-aerobic FFBs (206). (Reprinted from Water Research, Organic matter removal in combined anaerobic-aerobic fixed-film bioreactors, 37 (2003) 3561–3568, with permission from the copyright holders, Elsevier).

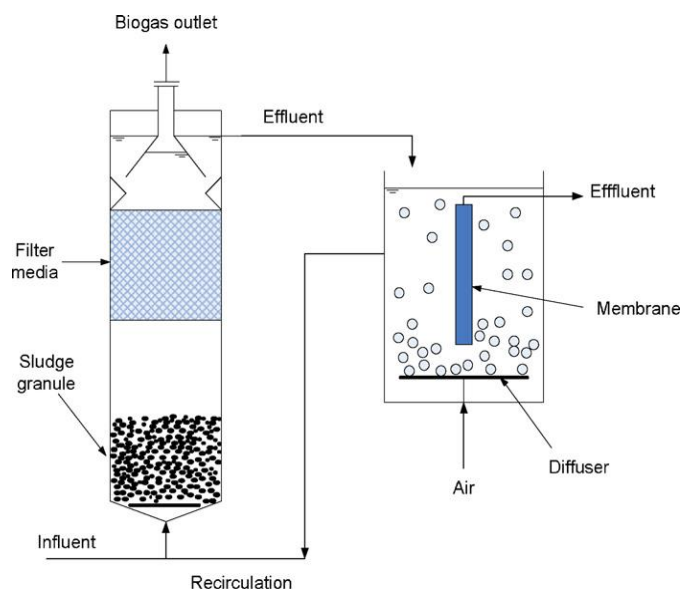


Fig. 16: Schematic representation of the UBF-aerobic MBR system (213). (Reprinted from Desalination, Simultaneous high-strength organic and nitrogen removal with combined anaerobic upflow bed filter and aerobic membrane bioreactor, 202 (2007) 114–121, with permission from the copyright holders, Elsevier).

Nevertheless, the system is not effective for the elimination of other nutrients. Seghezzi et al. (214) claimed that phosphorus and nitrogen are the main causes of eutrophication and have detrimental effects on receiving water. Accordingly, the removal of biological nutrients via the MBR system has to be enhanced. On a separate note, Bae et al. (37) proved that the modes of operation do not

influence the stable and high BOD removal of 97% or 98% for the MBR system. Moreover, membrane separation resulted in effluent free of SS. Other than these, the high BOD:TKN ratio of the influent caused the nitrifying bacteria not to be cultivated at an adequate rate. Thence, assimilation or synthesis of new cells devours nitrogen as its nutrient and, hence, the removal of nitrogen turned out to be fairly high

during the operation, reaching 96%. Furthermore, the constraint of the biological removal process caused by the high concentration of phosphorus in the influent resulted in low removal efficiency. Nonetheless, optimization of the system enabled the removal efficiency to reach 80%.

4 Challenges of handling polluted dairy in future

Demand for dairy products is foreseen to increase in the future and inevitably gear up the amount of wastewater from the industry. Every year, this industry increases its usage of chemical materials. Serious consequences may be faced by future generations if no new improved technologies are developed at a fast rate. As the main user and the significant generator of wastewater, the dairy industry can potentially reuse the wastewater. Boilers, cooling systems, and washing of plants are a few examples of the utilization of purified wastewater. Additionally, the dairy industry will enjoy a direct benefit from in-house treatment of wastewater with the prominent reduction in charge of levies for the reception of wastewater. For instance, 70% of the total savings from AD in the United Kingdom are attributed to the lower costs for discharge. Apart from that, the dairy industry will gain indirect benefits from fields that use effluents for irrigation of pastures. Therefore, efficient management of wastewater in the dairy industry is essential for these reasons.

5 Conclusion

For choosing an appropriate wastewater treatment method, a process assessment in addition to economic analysis is required. Effluent composition, concentrations, volumes produced, susceptibility to treatment, and the environmental impact are examples of important factors for selecting an efficient treatment method. The operational procedures and design must consider the fluctuation in the quantity and quality of wastewater from the dairy industry. According to the literature, the biological methods are revealed as the most economical approach in the removal of the organic since they are relatively easier to control. Nonetheless, the anaerobic methods are also outstanding as they have low rates of sludge production and have lower energy requirements. As no particular process of treating dairy wastewater may comply with the minimum requirements for discharge of effluent, application of a combined process that is particularly designed to treat specific dairy wastewater is necessitated. Over the past decades, awareness of the anaerobic-aerobic treatments has been increasing; this is attributed to several advantages: (i) low chemical consumption, (ii) low energy consumption, (iii) low sludge production, (iv) huge potential for resource recovery, (v) fewer equipment requirements, and (vi) high operational simplicity. Nevertheless, operational limitations are evident in the conventional anaerobic-aerobic systems, namely requirements for space, facilities to capture biogas, and long HRT. Accordingly, these restrictions are addressed through the development and application of new high-rate bioreactors that provide higher yields of methane for the production of biogas and ensure better removal of organic matters at shorter HRTs. Special care has been paid to the integrated anaerobic-aerobic bioreactors – a combination of

anaerobic and aerobic processes in a single bioreactor to minimize the limitations in terms of odors, minimal sludge production, and space. Compact integrated bioreactors are anticipated to treat an extensive range of industrial and municipal wastewater of high organic pollution. The simple, yet economical technology generates renewable energy and has a remarkable efficiency of treatment. Nonetheless, the majority of the integrated bioreactors stated in this study are not implemented on a large scale in the industry. Thus, a more extensive analysis of the performance and capability of these reactors is essential, particularly on a bigger scale. Improvements to the system are also fundamental with recommendations such as utilizing suspended carrier or packing mediums and installing a biogas capture system. In general, an anaerobic RBC integrated with an aerobic SBR system can achieve a considerable COD reduction to produce remarkable amounts of methane gas. High pH tolerance, reduced sludge formation, and stable COD removal performance of the UASB–AFB system make this system beneficial in the biological treatment of industrial wastewaters of medium-level pollution. Furthermore, the UASB–AFB configuration emerges as an attractive alternative from the technical, economical, and environmental perspectives; especially when space is a limiting factor. A significant COD removal in the treatment of highly polluted wastewater with high COD content can be achieved by integration of an anaerobic UBF and aerobic MBR systems at a relatively short HRT. Although the performance of this system is impressive, membrane fouling is an issue that should be addressed in this process. Conducting various researches is required for current biological methods of dairy wastewater treatment to enhance energy production and organic removal efficiency as well as reduce the operating cost and environmental impact.

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