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Review

The Application of an Upflow Anaerobic Sludge Blanket Reactor in the Treatment of Brewery and Dairy Wastewater: A Critical Review

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Abstract: Brewery (BW) and dairy (DW) wastewater are two types of agro-industrial wastewater that are generated in large amounts and, therefore, should be treated effectively and in an environmentally beneficial manner. Both these wastewater types are characterized by a high COD, BOD_5, and nutrient content, and conventional wastewater treatment methods such as an activated sludge process may prove to be inefficient due to the possibility of foaming, large biomass production, low activity at low temperatures, and risk of overloading the reactor with a load of organic pollutants. In the context of the described difficulties, anaerobic processes seem to be the best alternative. An interesting research area is the co-digestion of these wastewaters. However, this research direction, so far, has not been frequently reported. Given the gap in the current knowledge, this literature review aims to assess the possibility of BW and DW digestion in anaerobic reactors and provide up-to-date data on the post-treatment methods of effluent generated after the anaerobic digestion process. Despite numerous advantages, anaerobic treatment often requires post-effluent treatment to complete the treatment cycle.

Keywords: anaerobic digestion; brewery wastewater; dairy wastewater; co-digestion; biogas; wastewater treatment; UASB; renewable energy

Citation: Smetana, G.; Grosser, A. The Application of an Upflow Anaerobic Sludge Blanket Reactor in the Treatment of Brewery and Dairy Wastewater: A Critical Review. *Energies* **2024**, *17*, 1504. https://doi.org/10.3390/en17061504

Academic Editor: Marcin Dębowski

Received: 29 February 2024
Revised: 15 March 2024
Accepted: 18 March 2024
Published: 21 March 2024

1. Introduction

Water is a precious resource whose use is increasing every year, and this is directly linked to population growth and industrialization. An inevitable consequence of intensive water use is an increase in the volume of wastewater that is generated, which should be treated to reduce the threat to the environment and human health. However, despite legal regulations and the continuous development of treatment technologies, many countries still discharge untreated wastewater into the environment. It is estimated that 359.4×10^9 m^3 of wastewater is generated each year worldwide, of which 48% is untreated. However, the level of wastewater treatment depends on the geographic region and the level of economic development. Unfortunately, in developing countries, these values are much lower; for example, India produces nearly 50 billion litres of industrial and domestic wastewater per year, of which about 80% is in its raw form (without treatment) is discharged into lakes, rivers, and other water bodies [1–4]; in turn, in Poland, according to data from the Central Statistical Office in 2019, the amount of industrial and municipal wastewater requiring treatment was 2176.5 hm^3, of which 21% was treated only mechanically, and 5% was not treated at all [5].

The food industry is one of the most water-intensive industries and, consequently, generates the most significant amount of wastewater. It is estimated that the production of 1 m^3 of beer requires 4.7 to even 20 m^3 of water, mainly for rinsing, cooling, and brewing processes, and this, in turn, produces about 3–10 m^3 of wastewater [6–8]. The stages of beer production during which wastewater is generated include bottle washing, filtration, cleaning of equipment (vats, pipes, tanks, floors, etc.), packaging, etc. [9], and the total chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) of this wastewater type can vary, respectively, within the range of 2–32.5 g/L (attributed mainly to the presence of ethanol, carbohydrates, volatile fatty acids, and starch), 0.25–0.8 g/L, and 0.032–0.216 g/L [8–10]. On the other hand, dairy plants, depending on their size, the type of product, and the technological process of milk processing, use from 0.5 to 37 m^3 of water per m^3 of manufactured product, which means that the dairy industry generates large amounts of wastewater with highly variable organic characteristics [11,12]. For example, cheese production generates wastewater with a COD of 1–7.5 g-COD/L, whereas whey's COD can even be 50–70 g-COD/L [13].

Due to the high biochemical oxygen demand (BOD_5), COD, as well as wide pH range, the treatment of these wastewater types can be problematic with a conventional activated sludge process (CASP), and overloading can ensue [14,15]. A more practical and interesting option for the treatment of these wastewater types can be anaerobic digestion (AD) or, in particular, joint stabilization of brewery wastewater (BW) and dairy wastewater (DW) in the co-digestion process. Moreover, the BOD_5/COD rations of BW and DW are higher than 0.5 (0.6 to 0.7), meaning that they are both highly biodegradable [7,9,16]. High-rate anaerobic technologies such as an upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB), anaerobic granular bed baffled reactor (GRABBR), anaerobic fluidized bed (AFB), and anaerobic sequencing batch reactor (ASBR) are examples of the solutions that are currently being researched for and applied in wastewater treatment, and many of these technologies provide an appropriate level of COD and BOD_5 reductions [17,18]. A UASB is the oldest and by far the most proven technology, which was developed in the second half of the 20th century; however, it has disadvantages associated with a long start-up, low nitrogen and phosphorus removal, as well as low pathogen reduction [18,19]. Therefore, further effluent treatment is necessary to meet legislation standards. Even though a UASB is a well-studied technology, the research interest in this technology still grows, particularly in energy recovery production, joint treatment with other methods, the removal of a particular polluting compound, and microbial characterization of granular sludge [20].

So far, there is a lack of review articles discussing co-digestion in this reactor type. Based on the available data from the literature, this literature review provides information on the studies performed so far concerning the co-digestion in UASB reactors, focusing on the possibility of co-digesting BW and DW. Possible approaches to treat the effluent after digestion in a UASB are also within the scope of this literature review.

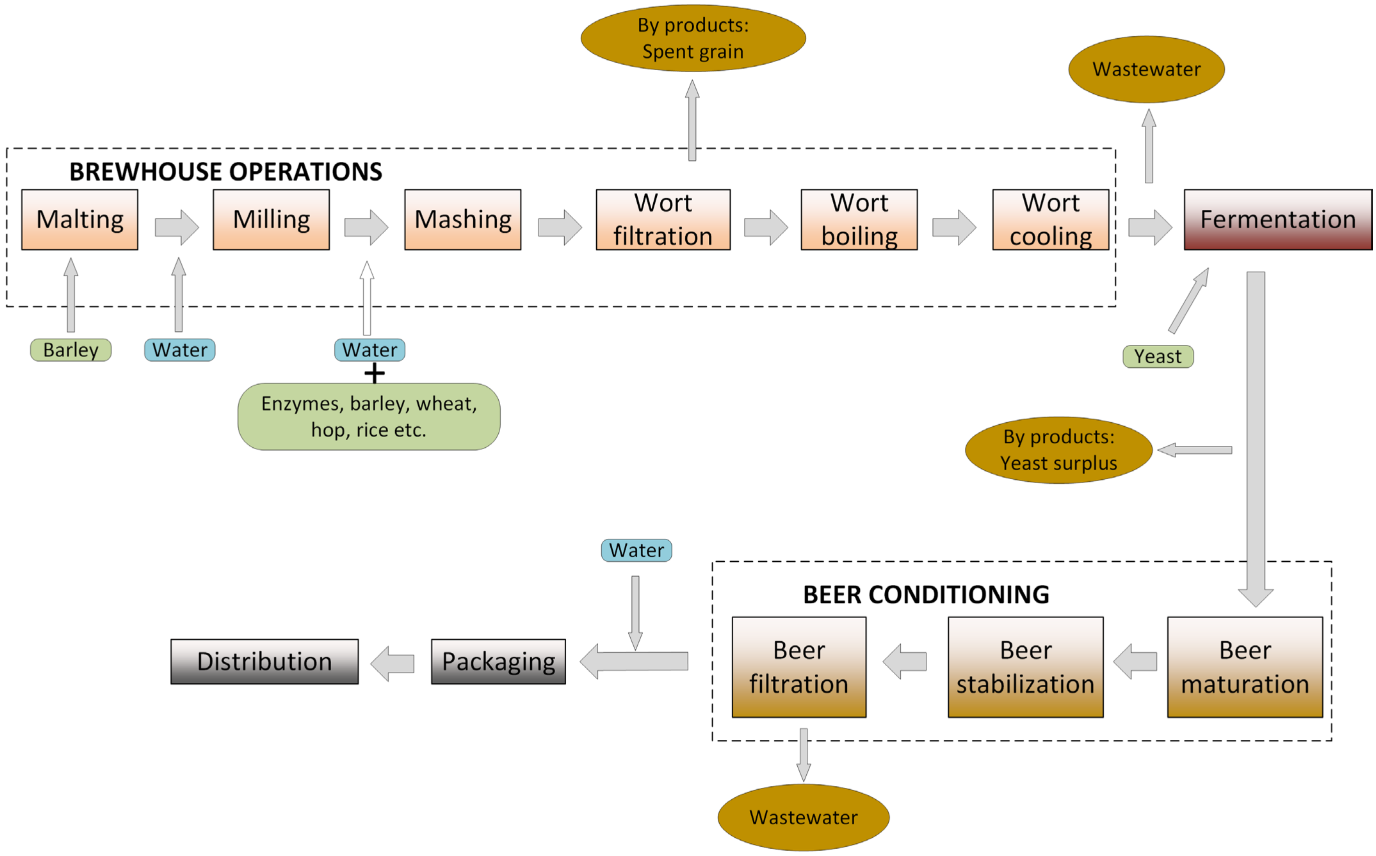
2. Brewery and Dairy Wastewater

2.1. Brewery Wastewater: Origin and Characterization

Compared to tea, coffee, and carbonated drinks, beer is the oldest and fifth most consumed beverage in the world, and breweries require an average of 3–10 L of freshwater per 1 L of beer. This intensive water use is associated with significant wastewater production [21]. Beer is produced through alcohol fermentation by a selected yeast species of the *Saccharomyces* genera (usually *Saccharomyces cerevisiae*). The wort is mainly prepared from barley, to which maize with hop flowers or their derivatives are added along with water [7]. Two distinct aims of water use in the brewing industry can be highlighted [22]:

- As a main ingredient of the beer;
- For brewing processes that include steam rinsing, cooling, cleaning a brewing house and floor before and after the operation, and beer packaging.

The figure below (Figure 1) presents the general technological process of beer production. As can be seen from the figure, the general technological process includes stages such as malting, mashing, milling, wort boiling, fermentation, beer conditioning, and packaging, with further distribution [7]. Wastewater is generated at the stages of wort boiling and cooling and beer conditioning.



By-product	Characteristics
Spent grain	Typical amount of solid in the mash is 25–30%. Can be sold as livestock feed for average 5 EUR/ton
Kieselguhr sludge	Disposal routes are agriculture and recycling with cost of 170 EUR /ton
Yeast surplus	Is recovered through natural sedimentation at the end of the fermentation and maturation. Sold as animal feed. The product has dry matter content dose to 10% w/w and beer losses are 1.5–3% of the total volume of produced beer
Waste labels	On average is produced in amounts of 282 kg per 1000 hl. The average disposal cost is 38 EUR /ton

Figure 1. General technological process of beer production; based on [7,23,24].

Besides wastewater, there also are solid wastes, including spent grain, a surplus of yeast, kieselguhr, 'hot' trub, and waste labels that are generated at the beer packaging stage [7,23,24]. One way to dispose of spent grains includes mixing them with excess yeast and cold break, a product of the tub separation after the wort cooling, and selling this mixture as livestock feed [24]. Other waste disposal practices concerning the spent grains include their application for low-value compost production, hydrolyzation to produce xylooligosaccharides, xylitol, and culture media that are rich with pentose [7]. It is estimated that about 3000 tons of surplus yeast is produced annually [25]. Surplus yeast has a 10% dry matter content, and its recovery is carried out with natural sedimentation at the end of the secondary fermentation and maturation [24]. Waste yeast has a high organic content and, therefore, can be used for AD to produce biogas [25]. Kieselguhr is a filtration additive that is used for conventional dead-end beer filtration, and its disposal routes include agriculture and recycling [24].

Beer production is associated with many microbial communities. The activity of different microorganisms and their presence depend on the stage of beer production, e.g., worting (*Enterobacteriaceae*), pitching yeast (*Obesumbacterium*, *Rhanella aquatilis*), and fermentation (*Lactobacillus*, *Pediococcus*). Fungi, such as Saccharomyces, are present throughout the three stages. Other stages such as conditioning and packaging are associated with the presence of bacterial genera such as *Selenomonas*, *Lactobacillus*, *Micrococcus*, *Pediococcus*, *Zymomonas*, *Pediococcus*, *Zymomonas*, *Pectinatus*, *Acetobacter*, *Megasphaera*, *Gluconobacter*, and *Zymophilus*. In the case of fungi, the mentioned stages are associated with the presence of *Saccharomyces*, *Hansenula*, *Pichia*, *Hanseniaspora*, *Torulopsis*, *Schizosaccharomyces*, *Brettanomyces*, and *Candida* [23].

BWs are medium-to-high-strength wastewaters that are characterized by high levels of nutrients such as nitrogen and phosphorus and, therefore, are difficult to treat with conventional methods, e.g., a CASP, which can be overloaded during treatment [26]. Another drawback of applying traditional methods to treat BW is the large amounts of waste sludge, which must be properly handled and disposed of according to local legislation standards [27].

The next table (Table 1) presents the typical characteristics of this wastewater type. The C/N ratio of this wastewater type varies within the range of 45–66.7 and higher [28–30]. The highest reported COD and BOD values are 115–125 g-COD/L and 65–80 g-BOD_5/L, respectively [31,32]. BW also has a wide pH range of 3.3–12 and a high temperature, which, in the case of opaque beer, can be within the range of 25–35 °C [27]. The alkalinity of BW can vary within the range of 0.27–2.45 g-$CaCO_3$/L [22,29]. In some old studies, it can be reported to be even less, i.e., 0.1 g-$CaCO_3$/L [33]. BW is characterized by a high content of soluble proteins and carbohydrates, and their respective values can be 0.5 g/L and 0.65 g/L [34].

Table 1. Some reported values of parameters of BW.

Type of Wastewater	Parameter							Reference
	pH (−)	**COD (g-COD/L)**	**BOD_5 (g-BOD_5/L)**	**TP (g/L)**	**TKN (g/L)**	**TSS (g/L)**	**Operational Temperature (°C)**	
Industrial brewery wastewater	3.3–6.3	8.24–20	Nd	16–124	0.0196–0.0336	2.901–3	Nd	[27]
Industrial brewery wastewater	4.5–12	2–6	1.2–3.6	10–50	25–80	0.2–1	18–40	[26]
Brewery wastewater from regulating reservoir	6.5 ± 0.2	2.25 ± 0.418	1.34 ± 0.335	Nd	Nd	0.48 ± 0.07	30–35	[35]
Raw brewery wastewater	7.5–8	1.3–2.3 (1) 1–2 (2)	0.65–0.97	3.2–4.3	Nd	Nd	Nd	[36]
Industrial brewery wastewater	10	2.083 (1) 1.726 (2)	1.375	0.0048	0.116	0.75	Nd	[37]
Industrial brewery wastewater	4.25	115–125	Nd	Nd	Nd	1.4–1.6	Nd	[31]
Synthetic brewery wastewater	5.2–6.2	8–14	Nd	0.02–0.09	0.08–0.28 (3)	0.5–1.3	35	[29]

Table 1. *Cont.*

Type of Wastewater	Parameter							Reference
	pH (−)	COD (g-COD/L)	BOD_5 (g-BOD_5/L)	TP (g/L)	TKN (g/L)	TSS (g/L)	Operational Temperature (°C)	
Industrial brewery wastewater	6.3	6	2.35	0.0005	0.09	Nd	35 ± 1	[28]
Raw brewery wastewater	3.5–4.5	80–90	65–80	0.09–0.1 (4)	0.11–0.21	0.1–0.15	36 ± 1	[32]

(1)—total COD; (2)—soluble COD; (3)—as total nitrogen (TN); (4)—as P-PO_4, Nd—no data.

2.2. Dairy Wastewater: Origin and Characterization

A variety of products, such as yoghurts, sour milk, desserts, cheeses, butter, creams, pasteurised milk, etc., are produced from raw milk in the dairy industry. The major distinction among these products is made based on whether there is a reuse of dairy by-products such as whey, full-fat milk, and evaporation of the remaining waste from the coagulum, milk, and whey powders [12]. Compared to other agro-industrial sectors, the dairy industries generate large amounts of wastewater with similarly high COD and BOD_5 concentrations [38]. For example, 10 kg of milk is required to produce 1 kg of cheese, and 9 kg of cheese whey is required. Cheese whey is deemed to be the most important waste product in the dairy industry because of its high COD and BOD_5 and the generated volume [39].

DWs contain both organic (spilt milk, spoiled milk, skimmed milk, and by-products such as whey, milk, and whey permeates) and inorganic (cleaning solutions of an alkaline or acidic character) compounds [12,16].

Dairy effluent contains such constituents as lactose, milk fat, proteins, lactic acid, and minerals such as sodium, potassium, calcium, and chloride [40]. Milk proteins, along with ionic species such as N-NH_4^+, NO_2^-, and NO_3^-, are the main constituents in the total nitrogen of this wastewater type, whereas the total phosphorus content is attributed to alkaline and acidic cleaning products [16]. The major protein in milk and, therefore, in DW is casein (for milk, 80% of the total protein content) [41]. Ions such as phosphate (PO_4^{3-}) and diphosphate ($P_2O_7^{4-}$) mainly contribute to the inorganic part of the phosphorus. However, they may exist in the organic form, as well. The C/N/P ratio of this wastewater type is about 200/3.5/1, signifying that DW lacks nitrogen, although AD can be used as a main treatment method [12]. As reported by [42], the content of carbohydrates and proteins in DW is 0.121 g/L and 0.388 g/L, respectively.

Typical dairy wastewater (Table 2) is characterized by high turbidity; a much higher temperature than municipal wastewater (average of 17–25 °C); a wide range of pH (4–9), BOD, and COD values of 0. 24–5.9 g-BOD_5/L and 0.5–10.4 g-COD/L, respectively; TN of 3.7–6%-BOD; TP of 0.6–0.7%-BOD; and low alkalinity (within the range of 0.213–1.55 g-$CaCO_3$/L), which is comparable with that of BW. The highest COD and BOD_5 values for DW are reported to be related to cheese whey, which can be 50–102.1 g/L and 27–60 g/L [12,43].

Table 2. Some reported values of different DW parameters.

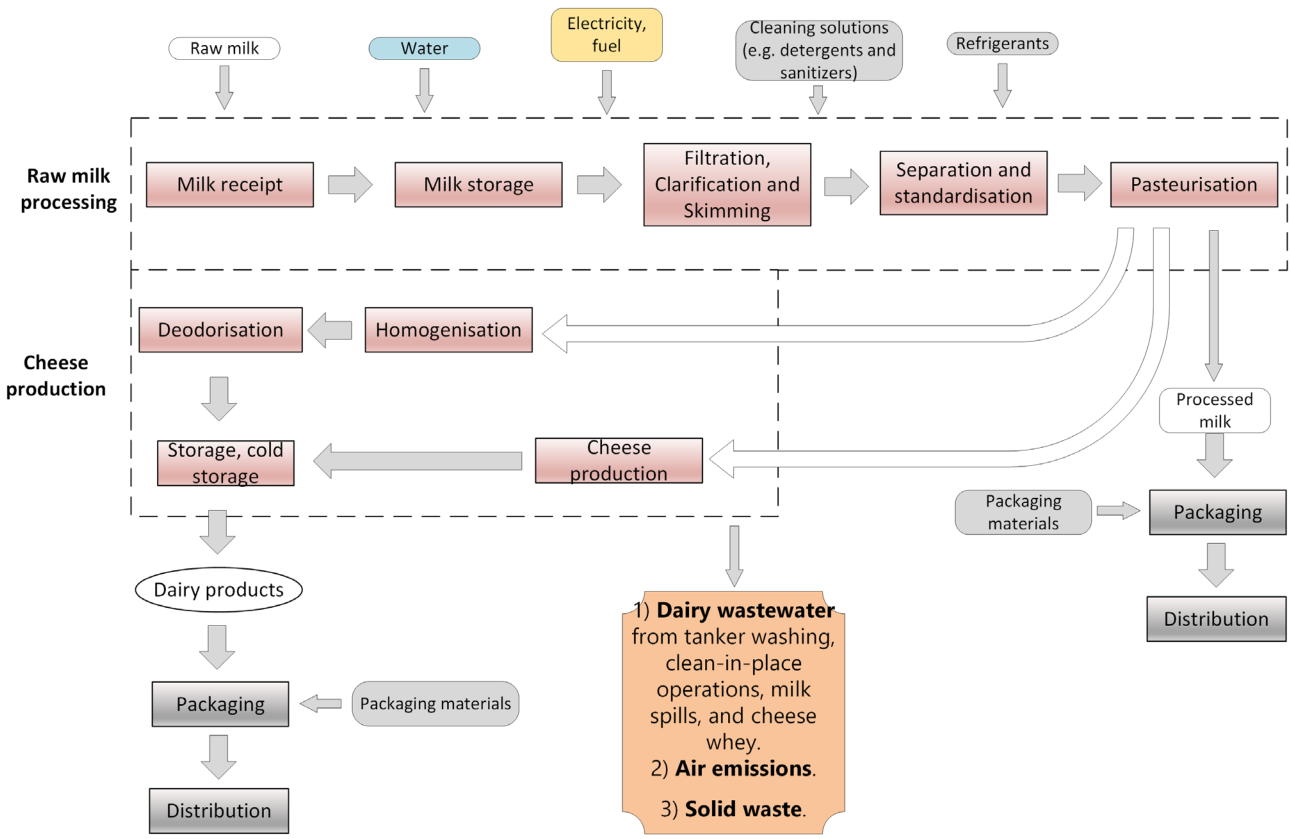
Type of DW	Parameter						Reference
	pH (−)	COD (g-COD/L)	BOD_5 (g-BOD_5/L)	TP (g/L)	TKN (g/L)	TSS (g/L)	
Synthetic	7.1	5	2.8	Nd	16.5	Nd	[38]
Mixed dairy	4.11	0.5–10.4	0.24–5.9	0–0.06	0.03–0.7	0.06–5.8	[12]
Milk processing effluent	Nd	2	1.5	0.003	Nd	Nd	[40]
Nd	5.9–6.5	1.98–3.32	1.08–1.58	0.06–0.08	Nd	2.4–2.95	[44]
Mixture of final whey effluent, water used for cleaning, and sanitary wastewater	7.75 ± 0.6	2.499 ± 0.812	Nd	0.0207 ± 0.0096	0.12 ± 0.01	Nd	[45]
Nd	7.9	3.38	1.94	0.022	0.051	0.83	[46]

Nd—no data.

In the dairy industry, wastewater generation is mainly attributed to such processes as milk receiving, milk storage, milk processing (pasteurisation, homogenisation, separation, and clarification, etc.), and cleaning operations (clean-in-place practices and cleaning of equipment, floors, rooms, trucks) [16,40]. Hence, three major wastewater categories that originate in the dairy industry can be mentioned [12]:

- Processing water is generated during milk cooling, and it is mainly a clean condensate that can, however, contain volatile substances, as well as milk and whey droplets. It can be directed to discharge along with stormwater after minimal treatment in most cases.
- Cleaning wastewater (clean-in-place effluent) is generated from cleaning procedures such as equipment cleaning, milk and whey spillage cleaning, and clean-in-place practices. This wastewater category is highly polluted and requires further treatment.
- Sanitary wastewater is generated in showers and toilets, and it is similar to municipal wastewater as far as its composition is concerned. This wastewater category is a good nitrogen source that can be used for nutrient stabilisation during secondary treatment.

It should be pointed out that the technological process scheme depends on the type of product (whether it is butter, cheese, pasteurised milk, etc.), and an exemplary process diagram (for cheese production) is presented in the next figure (Figure 2) [47]. As far as solely raw milk processing is concerned, milk is first delivered from farms to the milk receiving points and then analysed in relation to its content of fats, proteins, acidity, etc. Then, the milk is stored in milk silos at a temperature of 4–6 °C. The next steps include filtering and clarification to remove components such as dust, soil, sand, and protein coagulates, followed by skimming conducted by centrifugation. After filtration, clarification and skimming of the milk are performed in a standardised manner, i.e., the content of fats is adjusted to produce whole and low-fat milk and then pasteurised at a temperature of 72–75 °C for 15 sec or at 61.5 °C for 30 min to remove pathogens (mostly *Mycobacterium bovis*) [43].



Main waste by-product	Source	Characteristic	Potential direction of use
Buttermilk	created when cream is processed into butter	Water 91–92%, lactose3.8–4.2%, nitrogenous compounds3–3.4%, Fat 0.1–1% other mineral compounds (including calcium compounds calcium) 0.7%	intermediate product for the production of food buttermilk or certain types of processed cheese
Whey	created by processing milk into cheese	Sweet (rennet) whey - produced in hard cheeses, semi-hard cheeses, and soft and rennet casein. Its pH is in the range of 5.9–6.5 acid whey, which is formed in the production of cottage cheese. Its pH is in the range of 3.6–4.6 casein whey is formed in the production of casein with a pH equal to 4.6–4.7. TS 4.5–7.3%, fat 0.02–0.4%, protein 0.4–1.1%, Carbohydrates, mainly lactose 4–5% minerals 0.4–0.8% COD up to 60,000 mg/L BZT5 up to 35,000 mg/l TKN up to 600 mg/L	❑ animal feed; ❑ processed into a number of products such as: ❑ a bread ingredient; ❑ Whey beverages; ❑ Nutritional products (like for fitness Purpose)- e.g. Galacto-oligosaccharides biocatalyses by *Kluyveromyces lactis, Bacillus circulans, Bifidobacterium bifidum*, *Aspergillus oryzae*, and *Streptococcus thermophiles* ❑ protein-based product solution, - e.g., Nutrilac®; ❑ biodegradable materials, bioplastics, especially polyhydroxyalkanoates - e.g., cultivation with *Ralstonia eutropha* DSM545, *Pseudomonas hydrogenovor*; ❑ Biofuels such as: ❑ biogas; ❑ ethanol - e.g., whey powder and *Kluyveromyces marxianus* DSMZ-7239; ❑ butanol - e.g., from milk whey with Clostridium acetobutylicum DSM 792; ❑ Hydrogen - e.g., Synergistic use of *Clostridium* and *Thermoanaerobacterium*; ❑ Single cel protein - e.g., Cultivation with lactose fermenting microorganisms, mainly yeasts; ❑ Organic acid - e.g. citric acid from milk whey and *Aspergillus niger* ATCC9642 ❑ Bioactive peptides - e.g., using of the latex from *Maclura pomifera*; ❑ Polysaccharides - e.g., lactose from whey permeate and *Xanthomonas campestris*; ❑ Enzymes production – e.g., Proteases during grown on the whey *Serratia marcescens*;
Dairy processing sludge	Created during wastewater treatment	Characteristics depend on the wastewater treatment method	compost, irrigation, biogas production, land spread, grassland and arable organic fertiliser, „char-based materials"

Figure 2. General process diagram in dairy industry for cheese production, with inputs and outputs; based on [40,43,48–52].

3. The UASB Treatment Technology

3.1. UASB Reactor and Operational Conditions

A UASB is a high-rate reactor that was developed in the Netherlands in the second part of the 20th century. In comparison to the traditional AD systems, it allows for the application of a high organic loading rate (OLR) with the same volume of digester and with similar or higher COD and nutrient removal [18]. This reactor type can efficiently treat high-strength wastewaters such as BW, DW, sugarcane vinasse, paper mill wastewater (PMW), and various other industrial wastewaters that are characterized by high COD and BOD_5 values and which are easily biodegradable (BOD_5/COD > 0.5) [53]. The main feature that distinguishes this AD system from others is the formation of a dense granular sludge bed at the bottom of the reactor that contains organic and inorganic parts, as well as various bacterial consortia, which decomposes complex organic substrates to simpler ones (e.g., methane and carbon dioxide). The granules form due to the bacterial growth and accumulation of suspended solids that come with the incoming stream, and a supporting material is not required for the process [18,19,54]. The structure of the granules (Figure 3) is layered, i.e., the inner layer contains methanogenic microorganisms, whereas the outer one contains hydrolytic and acidogenic bacteria [53,55].

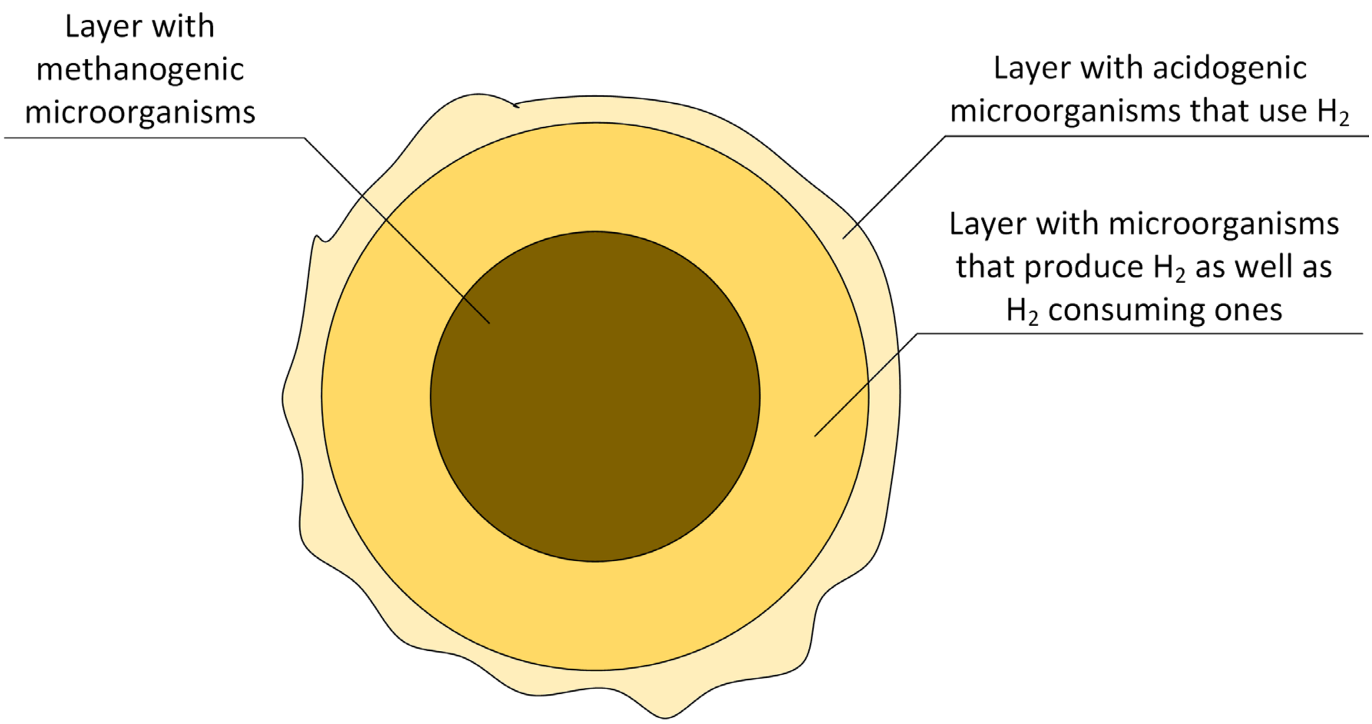


Figure 3. The structure of UASB granules; based on [55].

This granular sludge possesses excellent settling properties (its sludge-effluent separation is much more efficient) with highly active microbial populations [56]. Additionally, due to the intrinsic design of this reactor type, forced mixing is not required, and the natural turbulence that arises because the sludge is mixed with produced and buoyed-up gas bubbles provides sufficient biomass contact [18]. In this reactor (Figure 4), as the name suggests, the inflow stream is supplied vertically up from the bottom along the reactor height, where at the end, it meets the gas–liquid–solid separator (GLSS), an important element of this reactor type [18,19,54].

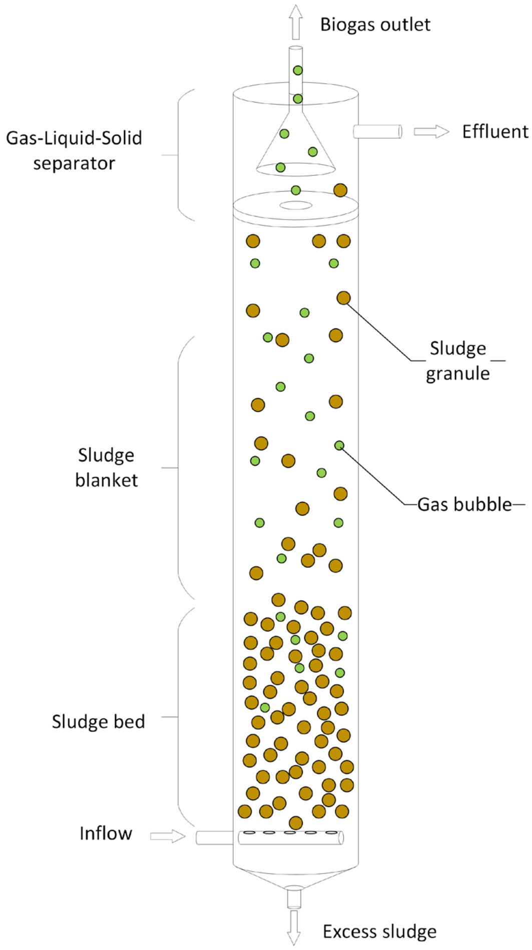


Figure 4. Simplified diagram of UASB reactor; based on [18,54].

The GLSS starts with a baffle that prevents the excessive washout of granules and redirects the gas bubbles towards the funnel like a gas collection part [54]. The UASB reactor can be seeded with activated sludge, digested sludge (inoculum), and anaerobic, granular, or flocculent sludges. Filling the UASB reactor up to 10 to 30% of its volume with the seeding active biomass is required to ensure a successful start-up. Depending on the seed and operational conditions, the dense sludge bed and more dispersed sludge blanket zones form after 2–8 months [18,53]. The anaerobic microorganisms that grow in the sludge bed actively use organic substances such as substrates, and the production of methane and carbon dioxide that find their way out of the reactor from the biogas outlet located at the very top occurs [18]. As was reported in a recent study that concerned the composition of the bacterial community in an internal circulation reactor (IC) or, otherwise, vertically integrated two UASB reactors, the most dominant phylum is *Proteobacteria* (22.85–32.70%). Other present phyla were *Bacteroidetes* (16.62–16.88%), *Chloroflexi* (12.55–24.57%), *Firmicutes* (6.07–8.94%), *Synergistetes*, *Spirochaetae*, *Thermotogae*, *Actinobacteria*, *Parcubacteria*, and *Acidobacteria*. Phyla such as *Longilinea*, *Desulfomicrobium*, *Caldithrix*, and *Geobacter* were also present in the reactor but in minor proportions. Proteobacteria play a crucial role in BW treatment, and their high abundance in the reactor leads to high organic matter degradation [57]. Similar results were obtained in another study which concerned garlic wastewater treatment, i.e., the *Proteobacteria* abundance was 30.05–47.57% [58].

The microbial community changes during wastewater treatment and depends mainly on the operational parameters of the AD, the process inhibitors, and the type of wastewater [53,59]. After the start-up stage and stabilization of UASB reactors treating dairy wastewater, the diversity of the microbial community decreases and begins to be dominated by four major phyla, namely, *Chloroflexi*, *Firmicutes*, *Proteobacteria,* and *Bacteroidetes*, which is mainly because they perform essential metabolic functions in the first three phases of AD [59–61]. As reported by Chen et al. [62], the ratio of *Firmicutes* to *Bacteroidetes* population can be an important indicator of process stability, as *Firmicutes* dominate the bacterial community during stable process operation, while a *Bacteroidetes* dominance indicates an overloading of the reactors. It is also worth mentioning that some research reports also mention a significant participation in the bacterial population of the *Synergistetes* phyla, which are asaccharolytic microorganisms that exhibit the ability to degrade proteins, peptides, and amino acids, and *Actinobacteria* phyla [59,60]. In addition to the abovementioned phyla, *Ignavibacteria* and *Caldiserica* are also isolated in UASB reactors. The former represent iron-reducing bacteria. The second are sulphate-reducing bacteria (SRB), which also show the ability to reduce sulphur compounds [61]. It is also worth noting that among both *Synergistetes* and *Firmicutes* phyles, bacteria that are capable of decomposing complex organic matter and producing hydrogen and carbon dioxide following the decomposition of lactic acid or acetic acid have been identified [60].

As for the dynamics of the Archaea domain, changes are observed. Some sources mention the dominance in the first months of the process of the acetoclastic methanogenic archaea (genus *Methanosaeta*, order *Methanosarcinales*), whose abundance decreases over time in favour of hydrogenotrophic methanogens of the genera *Methanobacterium* and *Methanobrevibacter*. This may be dictated by the hydrogenotrophic methanogens being characterized by higher metabolic flexibility because they have more excellent resistance and tolerance to unfavourable environmental conditions, such as a high content of volatile fatty acids [60].

An undoubted advantage of the microbial community in UASB reactors is that it can adapt to sudden changes in operating parameters [53]. For example, after an accidental introduction, along with a stream of dairy wastewater, of alkaline wastewater from the washing of the installation, an increase in the dominance of *Clostridia* is observed in the initial phase, which is associated with their resistance to cell lysis in the event of an increase in pH. A decrease in the methanogenic activity is also observed. However, the microbial population returns to equilibrium after some time and regains its methanogenic activity. The main bacteria and archaea that may be involved in the AD process are shown in Figure 5.

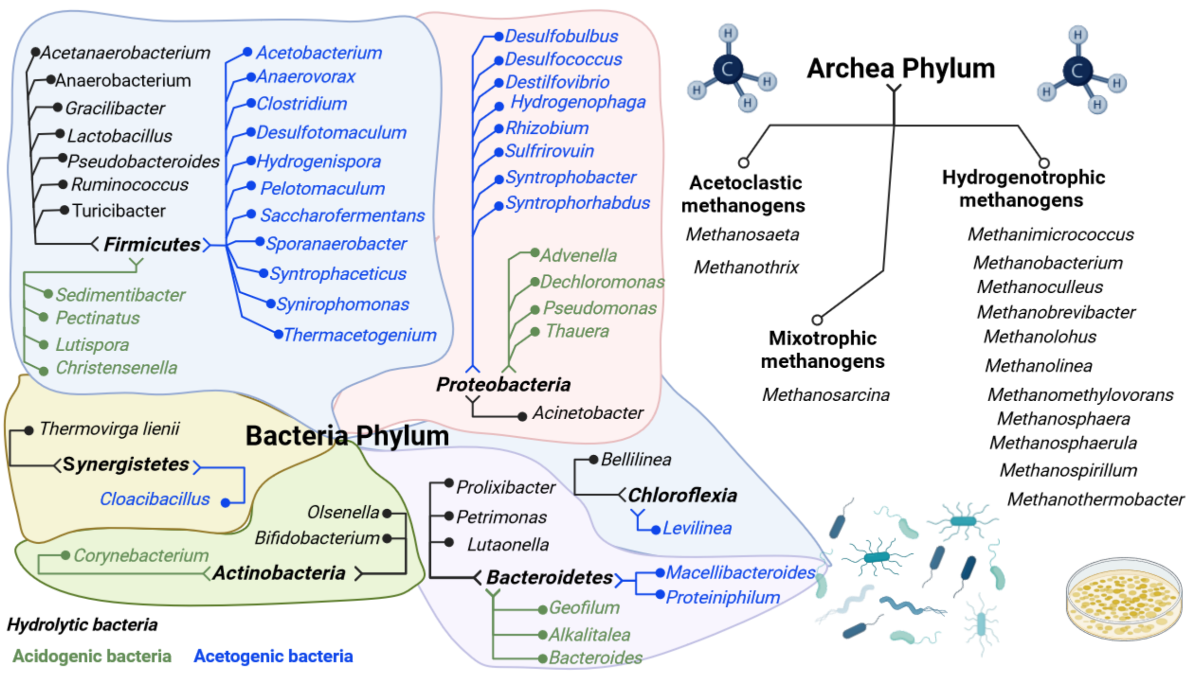


Figure 5. The main bacteria and archaea that are involved in the AD process; based on [59].

The next table (Table 3) mentions some recently reported studies concerning AD using a UASB.

Table 3. Some recently reported studies relating to UASB.

Substrate	Operational Temperature, (°C)	Influent COD, (g-COD/L)	COD Removal, (%)	OLR, (g-COD/L·d)	HRT, (h)	Digestion Duration, (d)	Seeding Sludge	Reference
Glutamate-rich wastewater	35	2	90–95	16	2–48	180	Granular sludge from a full-scale UASB that treats starch wastewater	[63]
Recycled PMW	37 ± 2	4.42–5.90	70–80.7	5.18	15.14	130	Granular sludge from a full-scale UASB digester that treats industrial wastewater	[64]
Municipal sewage sludge	16.5 ± 2	Nd	62–75	Nd	16, 24, 36	120	Inoculum sludge from a full-scale mesophilic anaerobic digester	[65]
Municipal primary effluent	19 ± 1	0.096–0.260 *	58–70 (1)	Nd	8, 10, 12	105	Anaerobic digested sludge from WWTP operated at 35 °C and fed with municipal primary effluent and glucose	[66]
Toilet wastewater	35	Nd	75.6 ± 6.0	16	6	250	Nd	[65]
BW	35	0.6–2.51	70–94	Nd	Nd	30	Activated sludge	[67]
DW	>25	Nd	75 (2)–94 (3)	2.5, 4.5, 8.6, 11.4	Nd	154	Nd	[68]
Synthetic starch wastewater	35 ± 1	1	75–95	0.5–8	3, 6, 8, 12, 24 and 48	280	Granular sludge from a full-scale UASB reactor treating BW	[69]
Chocolate wastewater	15, 20, 25, and 30	6.2 *	39–94	2–6	6	42–65	Anaerobic sludge from the secondary lamella settler of a low-temperature pilot-scale UASB reactor	[70]
BW	20–30.5	1.096–8.926	78.97	Nd	Nd	15	Nd	[71]

*—same as TCOD; (1)—same as TCOD removal; (2)—conventional UASB; (3)—modified UASB; Nd—not determined.

The efficiency and overall stability of the UASB system depend on the operational conditions. Among the most important ones, the pH, buffer capacity (alkalinity), operational temperature, HRT, OLR, and upflow velocity can be mentioned. AD in a UASB can be performed at psychrophilic (less than 20 °C), mesophilic (from 30 to 40 °C), and thermophilic (from 55 to 58 °C) operational temperatures [18]. The mesophilic temperature is, by far, the most chosen operational temperature due to its compromise between energy investments, process stability, and good biogas production. To obtain a good-quality granular sludge bed, a pH close to neutrality and high alkalinity is required [53]. To support a proper structure of the granules and avoid their washing out from the AD system, an upflow velocity within the range of 0.5 to 1 m/h is required [53–55]. However, other upper ranges of 1.5 m/h and even 6 m/h are also reported in other studies [55,56]. As is pointed out in [53], the treatment of particularly COD-loaded (more than 100 g-COD/L) wastewaters and substrates requires the adaptation of a longer HRT; however, this is contributed by a good methane yield compared to a lower OLR.

3.2. Advantages and Limitations of the Technology

The UASB technology has various advantageous features that differ from other technologies that are available today. As highlighted in the following table (Table 4), the main unique feature of this reactor is the granular sludge bed, which is dense and rich, with active microorganisms which can digest a variety of highly biodegradable substrates at a high OLR and short HRT, providing good COD removal [53]. Thus, a high reactor volume is not required when a high OLR is applied [19]. However, the nitrogen and phosphorus removal efficiency may be unsatisfactory with this technology, and post-treatment of the UASB effluent is required [16]. Additionally, effluents from an anaerobic treatment can often contain solubilised organic matter that contributes to COD and hydrogen sulphide (H_2S) [72]. Regarding DW, its treatment in a UASB is often combined with an aerobic treatment that can provide the remaining COD and nutrient removal [16]. The second most important limitation is the rather long start-up period associated with the granules' long formation. It was reported that the long start-up period could be shortened with divalent and trivalent cation addition, which, as suggested, neutralize negative charges on the surface of bacteria and increase their mutual adhesiveness. Besides divalent and trivalent cation application, other reported start-up improvement solutions include a water extract from *Moringa oleifera* seeds (WEMOS), chitosan, cationic, and hybrid organic–inorganic polymers, polyvinyl-alcohol (PVA) bead application as inert material, and lastly, a zero-valent-iron (ZVU) bed [18].

Table 4. Advantages and drawbacks of UASB treatment [18,19,53].

Advantages	Limitations
Granular sludge beds provide high biomass content with active microorganisms; therefore, high OLR with high COD removal efficiency are supported.	Long start-up period, from 2 to 8 months, highly dependent on OLR and operational temperature.
Support material is not required.	Sludge floatation, disintegration, and washout from a system can ensue.
Shorter retention time and easy manipulation.	Nitrogen, phosphorus, and pathogen removal efficiency may be low, and post-effluent treatment may be required, especially when high-COD wastewaters are treated.
No external mixing is required due to production of gas bubbles that provide natural turbulence.	Foul odour that can be attributed to hydrogen sulphide production, especially when wastewaters with high sulphur content are treated.
Lower energy consumption compared to aerobic processes and reduced sludge production.	
Technology is old, well developed, and popular (more than 1000 reactors have been installed worldwide) and provides satisfactory COD removal efficiencies for many types of high-strength wastewaters.	
Good treatment efficiency in tropical regions. It is a very flexible technology that can be applied efficiently at both large and small scales.	

3.3. Co-Digestion in UASB

Co-digestion is a good practice to improve the stability of the AD process, for example by introducing additional nutrients and necessary trace minerals or diluting toxic and inhibitory compounds. For instance, VFA and ammonium nitrogen accumulations, in particular ionised ammonium ($N\text{-}NH_4^+$) and free ammonium nitrogen (FAN), which are reported to be the major causes of the process imbalance, can be eliminated if proper C/N is maintained by introducing an additional co-digestion substrate [73]. The following table (Table 5) highlights some advantages and disadvantages of the co-digestion process.

Table 5. Some advantages and disadvantages of the co-digestion process [43,74].

Advantages	Disadvantages
Microbial stability improvement	COD value increase in effluents
Improvement in nutrient balance	Sometimes, pre-treatment and a hygienist are required.
Reduction in greenhouse gas emissions	The requirement of proper mixing to produce a homogenous mixture
Dilution of toxic compounds	An optimal mixture ratio is difficult to obtain
Higher methane yield and OLR	Digestate, after the process, has restrictions in terms of its land application

A UASB has a great potential for incorporating a co-digestion process, as many studies show, because a combination of substrates and wastes can be simultaneously treated at a high OLR, thereby improving the digestion stability and reducing the need to use other energy-intensive treatment processes [39,53,75,76]. Improvements associated with the addition of a co-digestion substrate to a high-rate reactor along with the primary feedstock include pH stabilisation, particularly to within the range that is optimal for methanogenic microorganisms (6.5–8.2), biodegradability improvements of slow-to-degrade substrates, start-up period shortening, and biogas production improvements [77,78]. Other enhancements include an increase in the growth of methanogens due to the increase in organic loading, which becomes higher when an additional substrate is introduced [79].

As is pointed out by [53], the HRT is typically longer when an additional substrate is introduced to the main feedstock; for example, the HRT can be as high as 20–46.8 h in the case of landfill leachate and acid mine drainage co-digestion [80]. As far as the UASB reactor is concerned, most co-digestion studies are conducted at a mesophilic temperature [53]. As is also pointed out in [53], the current research on UASB co-digestion is focused on the application of substrates that are available locally and micronutrient addition (such as Fe, Co, Se, Mo, Ni) to co-digestion mixtures to improve the digestion performance. Among other novel research directions, solar pre-treatment of microalgae can be mentioned, with a 32% biomass solubilisation achieved [81]. Also, research on microbial populations in UASB reactors remains interesting, such as in a study on the co-digestion of synthetic wastewater with raw palm oil effluent [82].

Some recent studies show that co-digestion in UASB can improve the biogas yield while providing proper COD removal. For example, a study concerning UASB co-digestion of yard, floral, and kitchen wastes, as well as DW with sewage sludge (SS) and cow manure, showed a biogas production of 3–4.6 L, with COD removal of 76–86% [76]. Some recent studies about co-digestion in a UASB have also focused on applying algae biomass as a co-digestion substrate. For example, it was revealed that microalgal biomass co-digestion with domestic sewage showed a 25% increase in specific methane yield compared to the control (raw sewage), a good COD and nutrient removal, and a positive net energy balance [75].

An example of an old study, in which co-digestion in a UASB reactor was of concern, is the co-digestion of three different types of glycerol with potato processing wastewater, where increased biogas and methane productions, as well as a high COD removal (about 85%), were revealed [78]. Another study focused on the pre-treatment of wheat straw, whose digestion is conducted in batches, a UASB reactor, and seaweed hydrolysate as a co-substrate. Pre-treatment of the wheat straw improved the specific methane yield by 57% compared to the untreated control, and a high COD removal of 94% was observed for an OLR of 10 g-COD/L·d [83]. The Table 6 highlights some recently conducted studies related to co-digestion in a UASB reactor.

Table 6. Recent research related to UASB co-digestion.

Feedstock	Substrate	Operational Temperature, (°C)	HRT, (h)	OLR, (g-COD/L·d)	Biogas/Methane Production	COD Removal, (%)	Reference
SS	Microalgae biomass	Nd	7	0.65–0.71	309.4–375.1 (4)	70	[81]
Landfill leachate	Acid mine drainage	35 ± 1	8, 12, 20, 30, 46.8	1.08–4.2	1.589–1.805 *	69–75	[80]
Gin spent wash	Swine wastewater	36 ± 1	3.3	28.5	8.4 (1)	97	[84]
SS and cow manure	Kitchen waste, yard waste, floral waste, DW	36 ± 2	24	Nd	3–4.5 *	76–86	[76]
Blackwater	Food waste	35 ± 1	62.4	4.1, 5.1, 7, 10, 11.6	2.42 (2)	82.4–83.6	[85]
Coal gasification wastewater	Glucose	Nd	Nd	Nd	5 *	50.85	[86]
Primary sludge	Fruit peel waste (melon, papaya, pineapple)	35	24	Nd	650 ± 50 (3)	About 45	[87]
SS	Crude glycerol	35	Nd	Nd	223.8–368.8 (4)	Nd	[88]
Cheese whey	Liquid fraction of dairy manure	35	2.2	19.4	6.4 (2)	95	[39]
		36–37	10–20 (5)	10.107	Close to 1.4 *	Nd	[89]
Domestic wastewater	Food waste	35 ± 1	10 (5)	2–4.5	0.25 (2)	61–80	[90]
BW	Swine manure	37 ± 2	16–24	8.613	497.94 ± 10.01 (6)	75.54 ± 0.19	[91]
Poultry manure	Rice straw, ground corncob, peanut shell, sawdust	35	Nd	Nd	155.29–301.95 (4)	32.20–93.25	[92]
Cardboard	Waste yeast	35	Nd	Nd	125/71–228.91 (4)	Nd	[93]

*—in (L/d); (1)—in (L-CH_4/d); (2)—in (m^3/m^3·d); (3)—biohydrogen production in (mL-BH_2/g-$COD_{removed}$); (4)—in (mL/g-VS); (5)—in (d); (6)—mL-CH_4/L·d; Nd—no data.

4. Brewery and Dairy Wastewater Co-Digestion Potential in UASB Reactor

So far, the studies that examine the possibility of co-digesting BW with DW in a UASB are lacking. As was pointed out in the previous section, both these wastewater types are highly biodegradable and, depending on the technological process, have different organic characteristics that can influence the AD process. For example, cheese whey is a highly biodegradable substrate. Still, it lacks in alkalinity (lower than 2.5 g-$CaCO_3$/L), which can inhibit the digestion process and, in this case, the rate-limiting stage is methanogenesis, because the organic part of the waste exists mainly in a soluble form [39]. The optimal alkalinity value lies within the range of 2–5 g-$CaCO_3$/L [94]. BW is also characterized by a low alkalinity and high TSS content, as was pointed out in the previous section. A possible solution would be to add alkalinity using the following methods [39,43]:

- Application of chemicals such as sodium bicarbonate ($NaHCO_3$), potassium bicarbonate ($KHCO_3$), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), or calcium carbonate ($CaCO_3$).
- Dilution of a substrate.
- Addition of an additional substrate that can improve the organic characteristics.

Additionally, the digestion of DW, particularly cheese whey, in high-rate systems may inhibit biomass granulation and increase its washout from the reactor due to the excessive production of exopolymeric substances (EPS), which reduce the settleability of the biomass [37]. Besides washout, UASB treatment of DW, which contains a large amount of lipids, may also cause sludge floatation, mass transfer, and sludge settleability reductions. Less than 0.1 g/L of lipids is indicated to be optimal in DW for its proper treatment at a mesophilic temperature; however, its successful treatment when the lipid content was 1 g/L was also reported. Various methods for lipid degradation and ultimate solubilization are reported: extracellular enzyme application, Fenton oxidation, and ferrous iron addition [13].

As for an additional substrate addition to increase the digestion stability, wastes such as SS (alkalinity of 4.03 g-$CaCO_3$/L), piggery wastewater (1.05–7.52 g-$CaCO_3$/L), cattle manure (3.4 g-$CaCO_3$/L), food waste dairy manure (more than 3.1 g-$CaCO_3$/L), and food waste leachate (2.85 g-$CaCO_3$/L) can be used [95–97]. The substrate can be added as a third component to the BW/DW mixture in order to stabilize the C/N ratio and alkalinity. As mentioned in the sections concerning the characterization and origin of BW and DW, the C/N ratio of these wastes is rather high, so introducing an additional substrate to the co-digestion mixture may improve its digestion stability. As an example, [30] conducted the co-digestion of SS with BW and obtained an maximum optimum biogas volume of 126.67 L and a methane content in the biogas that was close to 68.6% at a mixing ratio of 25/75.

Another interesting co-substrate for BW/DW digestion is algae biomass (AB). AB has a low C/N content (usually within the range of 6–9.36), which is attributed to the high protein content and can contribute positively to the co-digestion mixture [98,99]. As was pointed out in [99], the previous assumption that synergism and, hence, methane production improvements are achieved by mixing different substrates in one co-digestion mixture is now substituted by another assumption that methane production is a function of the total OLR, and therefore, a variety of different substrates with a high C/N ratio can be used for AB co-digestion, including of BW and DW [99].

5. Possible Effluent Post-Treatment Approaches

As is pointed out by [75], there is a lack of studies that examine the post-treatment of UASB effluent. UASB effluent is often required to be post-treated, particularly in relation to nutrient and pathogen removal, to comply with stringent legislative standards associated with its discharge [53]. This reactor type was not designed for pathogenic removal. However, relatively good results are reported (the removal efficiency of helminth eggs is within the range of 60–90%) [100].

So far, as is presented in the following table (Table 7), a variety of effluent post-treatment approaches that are coupled with this reactor type have been developed [18,72,101,102].

Table 7. Current UASB effluent post-treatment methods [18,72,101,102].

UASB–Aerobic System	UASB–Anaerobic System	Other
UASB–activated sludge (UASB-AS), 2001	UASB–anaerobic sludge thickening and digestion (UASB-ASTD), 2004	UASB–constructed wetland (UASB-CW), 2005
UASB–sequencing batch reactor (UASB-SBR), 2001	UASB–anaerobic biofilm fluidized bed reactor (UASB-ABFBR), 1991	UASB–double filtration (UASB-DF), 2016
UASB–stabilising pod (UASB-SP), 1999	UASB–anaerobic hybrid process (UASB-AH), 1999	UASB–microbial fuel/electrolysis cells (UASB-MFCs/MECs), 2009
UASB–rotating biological contactor (UASB-RBC), 1999	UASB–anaerobic filter process (UASB-AF), 1997	UASB–moving bed biofilm reactor (UASB-MBBR), 2010
UASB–integrated fixed-film activated sludge (UASB-IFAS), 2016	Two-stage UASB process (UASB-UASB), 2000	UASB–advanced oxidative process (UASB-AOP), 2002
UASB–aerated biofilter (UASB-BF), 1996	UASB–expanded granular sludge bed reactor (UASB-EGSB), 2003	
UASB–membrane bioreactor (UASB-MBR), 2011–2013	UASB–dissolved air floatation (UASB-DAF), 1999	

Some of these post-treatment approaches, in particular UASB-AS, UASB-SBR, UASB-BF, UASB-UASB, UASB-MBR, and UASB-DF, are discussed in the following subchapters.

5.1. UASB–Activated Sludge (UASB-AS)

UASB-AS is an old effluent post-treatment approach that was first documented in 2001 [103]. The joint system consists of a UASB reactor coupled with a continuous flow aeration tank and a settling tank, from which the settled solids are directed back to the UASB reactor to continue their further digestion. The UASB serves two purposes in this system: an anaerobic reactor and a secondary clarifier. The following figure (Figure 6) presents the scheme of this post-treatment method [18,103].

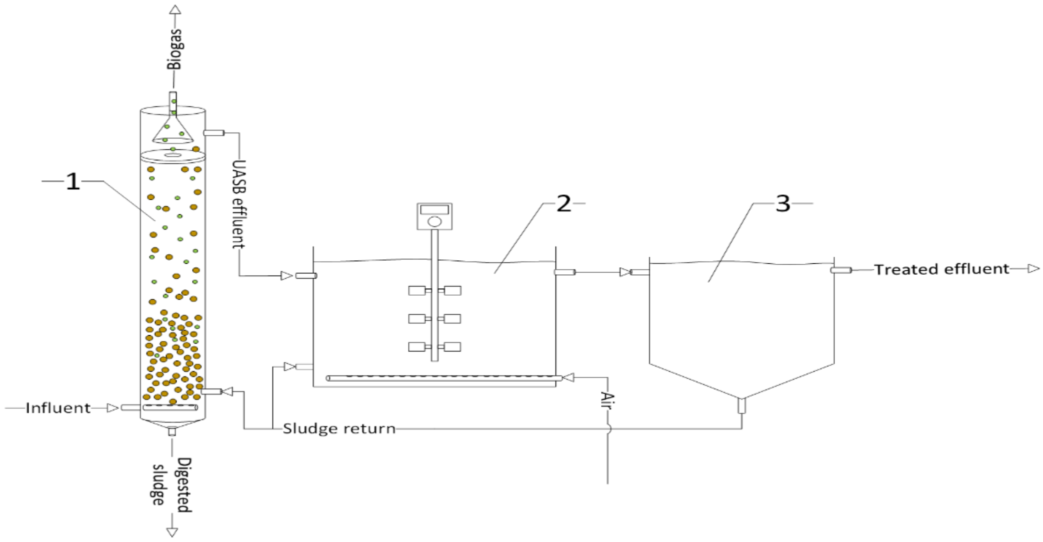


Figure 6. A diagram of the UASB-AS system: (1) a UASB reactor, (2) an aeration tank, and (3) a secondary clarifier; based on [18].

Many studies prove the feasibility of this solution. Good results regarding the COD, SCOD, and nutrient removal (0.051 g-COD/L, 0.025 g-SCOD/L, and 0.0031 g/L, respectively) were obtained in a study in which municipal SS was treated in warm-climate conditions (67–97% COD reduction and 87–93% nutrient reduction) [104]. In another study, DW was treated using such a system. A COD removal of 97.5% was observed after AS treatment of the UASB effluent [46]. Despite an excellent COD and nutrient removal efficiency, the UASB-AS system provided unsatisfactory total faecal coliform reduction; therefore, disinfection was required [18]. The following table (Table 8) provides information on studies conducted in relation to this post-effective treatment approach.

Table 8. The efficiencies of the UASB-AS system that were achieved in selected studies.

Type of Wastewater	Influent COD, (g-COD/L)	Influent N-NH_4^+, (g/L)	COD Reduction (UASB-AS), (%)	Nutrient Removal (UASB-AS), (%)	HRT_{UASB}, (h)	HRT_{AS}, (h)	OLR_{UASB}, (g-COD/L·d)	Operational Temperature of UASB, (°C)	Reference
Municipal wastewater	0.156–2.001	0.0243–0.048	67–97	87–93	6	6.3	Nd	30 ± 1	[104]
Pipe effluent of Arab Dairy Factory	3.383 ± 1.345	0.051 ± 0.0057 (1)	97.5	Nd	24	Nd	1.9–4.4	20	[46]
Municipal wastewater	2.5	0.095	89.1–91	69.4–96.2	13.9–56	9.84–24.24	1.1–3.8	25	[105]

(1)—as TKN; Nd—no data.

5.2. UASB–Sequencing Batch Reactor (UASB-SBR)

This post-effluent treatment approach is a modification of the previously discussed UASB-AS system, where the aeration tank and secondary clarifier, as shown in Figure 7, are substituted with a singular tank that works in cycles (usually fill, react, settle, decant, and idle) and which can be adjusted to work in aerobic, anaerobic, and anoxic conditions [18,102,106]. Recent research concerning this hybrid system shows good results in wastewater treatment. For example, excellent COD removal was achieved for treating high-concentration garlic processing wastewater, i.e., 45% for UASB and 96% for SBR. The TP and TN removals were 94.82% and 94.87%, respectively [58].

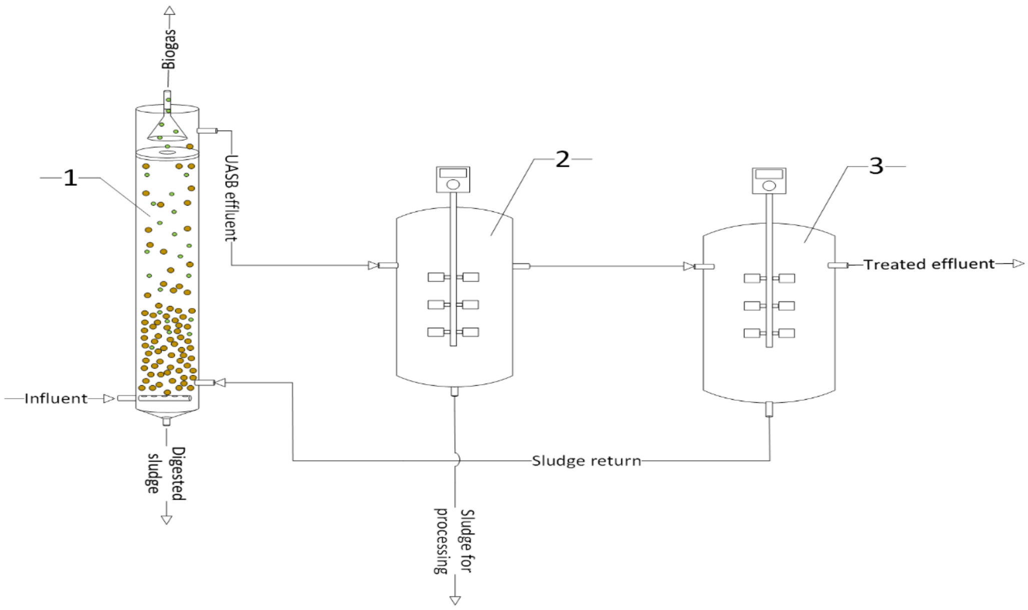


Figure 7. A diagram of the UASB-SBR system: (1) a UASB reactor, (2) a UASB effluent storage tank, and (3) an SBR; based on [18].

In another study, in which tannery wastewater was treated with a hybrid UASB-SBR–electrochemical oxidation (EO)–biological aerated filter (BAF) system, the maximum COD and N-NH_4^+ removals after SBR were both close to 80–83% at an HRT of 20 h [95]. The Table 9 presents the results of a selection of reported studies relating to the UASB-SBR process.

Table 9. Selected reported results for the UASB-SBR system.

Type of Wastewater	Influent COD, (g-COD/L)	Influent N-NH_4^+, (g/L)	COD Reduction (UASB-SBR), (%)	Nutrient Removal (UASB-SBR), (%)	HRT_{UASB}, (h)	HRT_{SBR}, (h)	OLR_{UASB}, (g-COD/L·d)	Operational Temperature of UASB, (°C)	Operational Temperature of SBR, (°C)	Reference
High-Concentration Garlic Processing Wastewater	9.8	Nd	99	94.82 $^{(1)}$, 87.07 $^{(2)}$ and 94.87 $^{(3)}$	45	12	Nd	35 ± 2	25	[58]
Tannery	8.3–9.25	0.285–330	98.9	93.8 $^{(3)}$	36–96	30 $^{(4)}$	2.23 ± 0.15	28 ± 3	Nd	[107]
Industrial and Domestic	Nd	Nd	94	100 $^{(5)}$, 77 $^{(3)}$, 65 $^{(1)}$	Nd	Nd	Nd	Nd	Nd	[106]
Piggery	1.5–6	0.55–0.85 $^{(6)}$	92	90 $^{(2)}$, 80 $^{(1)}$	Nd	Nd	Nd	24–26	24–26	[108]
Landfill Leachate	7.856–22.5	0.738–1.287	96.7	99.7	1–1.5	1.5	1.63–11.95	30–35	10.9–20.7	[109]

$^{(1)}$—TP removal; $^{(2)}$—N-NH_3 removal; $^{(3)}$—TN removal; $^{(4)}$—as SRT, expressed in (d); $^{(5)}$—N-NH_4^+ removal; $^{(6)}$ as N-NH_3; Nd—no data.

A new type of aerobic granules—oxygenic photogranules (OPG)—was recently discovered, which are spherical microbial aggregates that form in static (in scintillation vials) and dynamic (SBR) conditions from activated sludge in a few weeks when a light source of a sufficient intensity is provided [110,111]. The granules are named as they are because they produce oxygen through oxygenic photosynthesis, which is used by heterotrophic microorganisms that constitute the granules' centre (Figure 8). In contrast, the outer layer is occupied by cyanobacteria (mainly of the *Oscillatoria* genus) that primarily cause OPG formations [111].

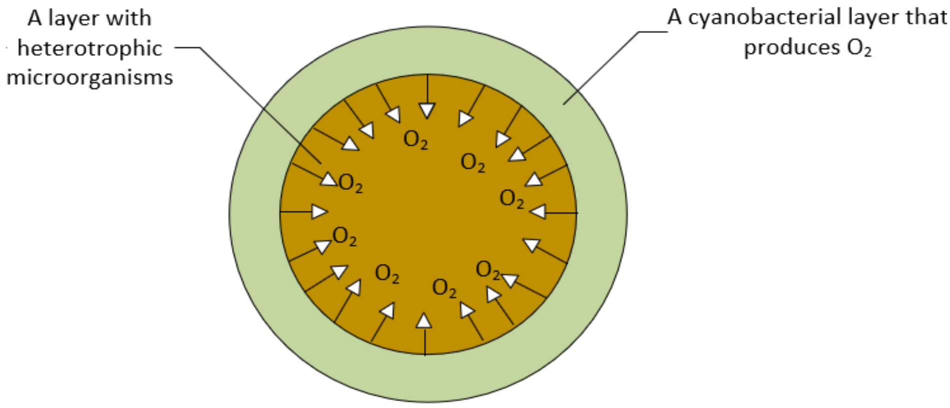


Figure 8. Simplified structure of OPGs; based on [111].

The SBR-OPGs system can potentially substitute the CASP process because of its in situ oxygen production, introducing great energy and financial savings. In a study conducted by [112], a specific oxygen production rate (SOPR) of 12.6–21.9 mg-O_2/g-VSS·h was observed. In another study, it was shown that the SBR-OPG system had a better COD and nutrient removal efficiency compared to the CASP process, i.e., 59.68%, 87.50%, and 85.37%, respectively, for COD, nitrate, and phosphate removals. In contrast, CASP had 49.90%, 80%, and 84.55%, respectively, for the mentioned parameters [113]. The granules also have a higher settling velocity compared to activated granular sludge (AGS), i.e., one that can be within the range of 26–91 m/h or even up to 360 m/h, as it is in the case of bald granules, whereas for AGS, the range is 10–40 m/h [110,114]. So far, a study concerning UASB effluent post-treatment with the SBR-OPG system has not been published, and it would be an interesting research direction, especially for effluent after BW and DW digestions, which are high-strength wastewaters.

5.3. UASB–Biofilter (UASB-BF)

In this hybrid system, a biofilter, which can be a trickling filter (TF) or an aerated filter (AEF), serves as biological packing media, in which biological decomposition takes place under aerobic conditions that are maintained by diffusion, forced aeration, as well as natural convection. Biofilm forms on the packing media, through which UASB effluent passes towards the reactor's bottom [18]. The Figure 9 presents an exemplary simplified diagram of the UASB-BF hybrid system [115].

The biofilter media can consist of materials such as polystyrene, sand, anthracite, zeolites, expanded clay, and a variety of organic waste materials, such as peanut shells, coconut fibres, woodchips, rice straw, and date palm fibres [116]. Other packing media such as Rotosponge, blast furnace slag, Rotopack, and downflow hanging sponge (DHS) were also studied [18]. The good performance of this hybrid system was shown in many early studies; for example, high COD and TN removal rates were achieved in a study concerning sewage water treatment, with an HRT of 5–12 h and OLR of 1–2 g-COD/L·d, i.e., a COD removal rate of more than 92% and 68–83% for TN removal [117]. Another study, in which a TF with Rotosponge packing media was used for UASB effluent treatment, showed excellent performance in relation to N-NH_4^+ removal, i.e., 80–95%, and the overall nitrogen removal was great with this packing media when the OLR was adjusted to 0.75 g-COD/L·d [118]. However, one recent study found that BF systems have low efficiency regarding nitrogen and phosphorus removal [119]. The best performance in terms of organic matter and nutrient removals was identified for a DHS, i.e., 92.01%, 82.26%, 91.02%, and 92.88%, respectively, for BOD, COD, TSS, and VSS removals [120]. A DHS accommodates a large surface area for microbial growth due to its structure, which is in the form of sponge cubes through which wastewater trickles. The natural drought of air downstream provides aeration, and no excess sludge removal is necessary [100]—the Table 10 presents information on studies related to the UASB-BF hybrid system.

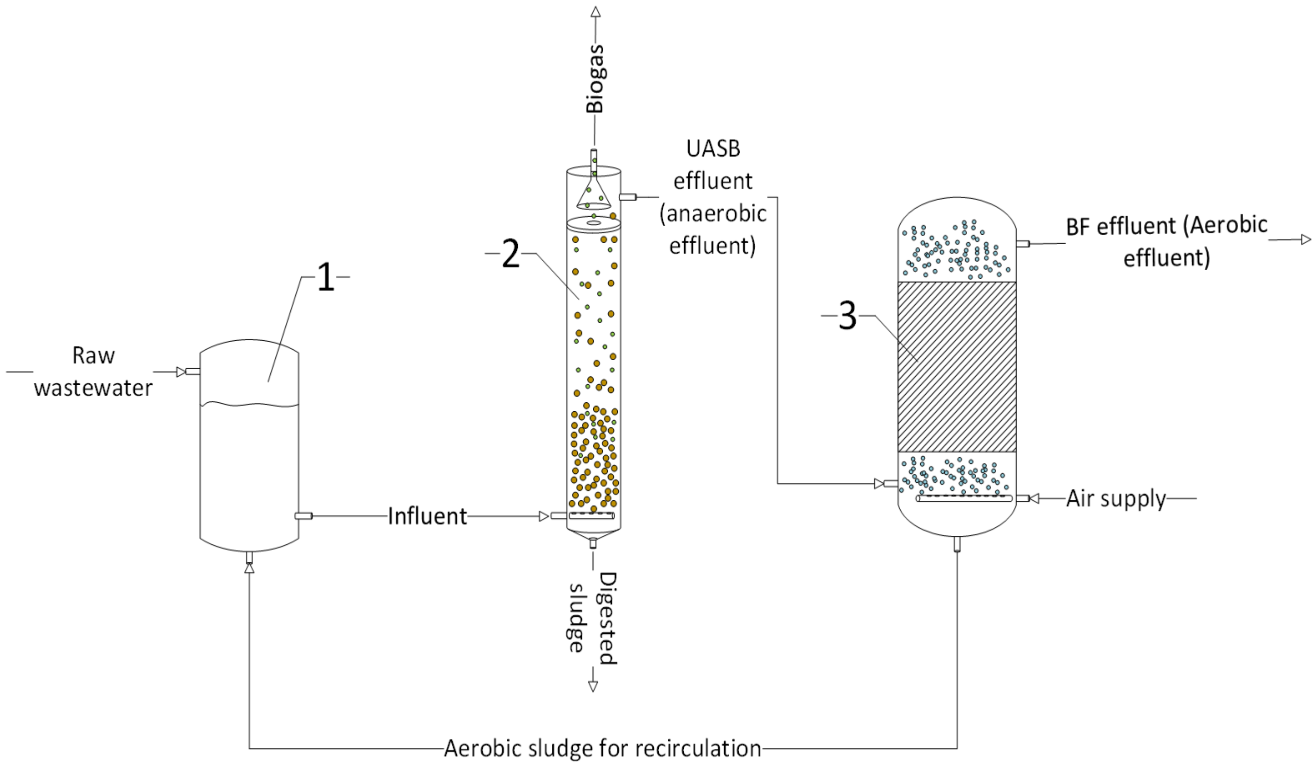


Figure 9. A diagram of the UASB-BF system: (1) a storage tank for raw wastewater, (2) a UASB reactor, and (3) a BF; based on [115].

Table 10. Studies related to the UASB-BF hybrid system.

Packing Media	Influent COD, (g-COD/L)	Influent N-NH_4^+, (g/L)	COD Reduction (UASB-BF), (%)	Nutrient Removal (UASB-BF), (%)	HRT_{UASB}, (h)	OLR_{UASB}, (g-COD/L·d)	Operational Temperature of UASB, (°C)	Reference
Nd	Nd	Nd	92	68–83	5, 8, 10, 12	1, 1.2, 1.5, 2	Nd	[117]
(a) TF–Rotosponge with a specific surface area of 132 m^2/m^3 (b) TF–Rotopack with a specific surface area of 29 m^2/m^3	0.2–0.7	Nd	85–90	80–95	9	1.2	Nd	[118]
DHS and final polishing unit (FPU)	0.589	Nd	82.26 (1) 74.35 (2)	Nd	8	1.52	Nd	[120]
Shredded waste plastic bottles	0.263 (3) 0.067 (4)	0.023	89.2–94.55 (3) 60.52–67.59 (4)	12.9–78.1 (5)	25	Nd	20 ± 3	[121]

(1)—for DHS, (2)—for FPU, (3)—for TCOD, (4)—for SCOD, (5)—for TN removal, Nd—no data.

5.4. Two-Staged UASB System (UASB-UASB)

A two-staged UASB system is a hybrid system in which two UASB reactors are connected in a series to improve digestion and increase removal efficiencies. The conditions are optimized depending on the reactor's purpose and the biomass type. For example, one UASB reactor can serve as a hydrolytic unit (which is usually the case), in which an intensive hydrolysis stage takes place, and the other as a methanogenic unit, to which the effluent from the first reactor is supplied to continue the digestion [18]. The division of the conditions into separate reactors can be fulfilled because microorganisms that take part in the AD process are classified into groups, i.e., hydrolytic, acidogenic, acetogenic, and methanogens, and their optimum growth conditions do not coincide [53]. The following figure (Figure 10) shows a simplified diagram depicting the two-staged UASB system, in which the first reactor is used as a hydrolytic upflow sludge blanket (HUSB) and the second one as a methanogenic upflow sludge blanket (MUSB).

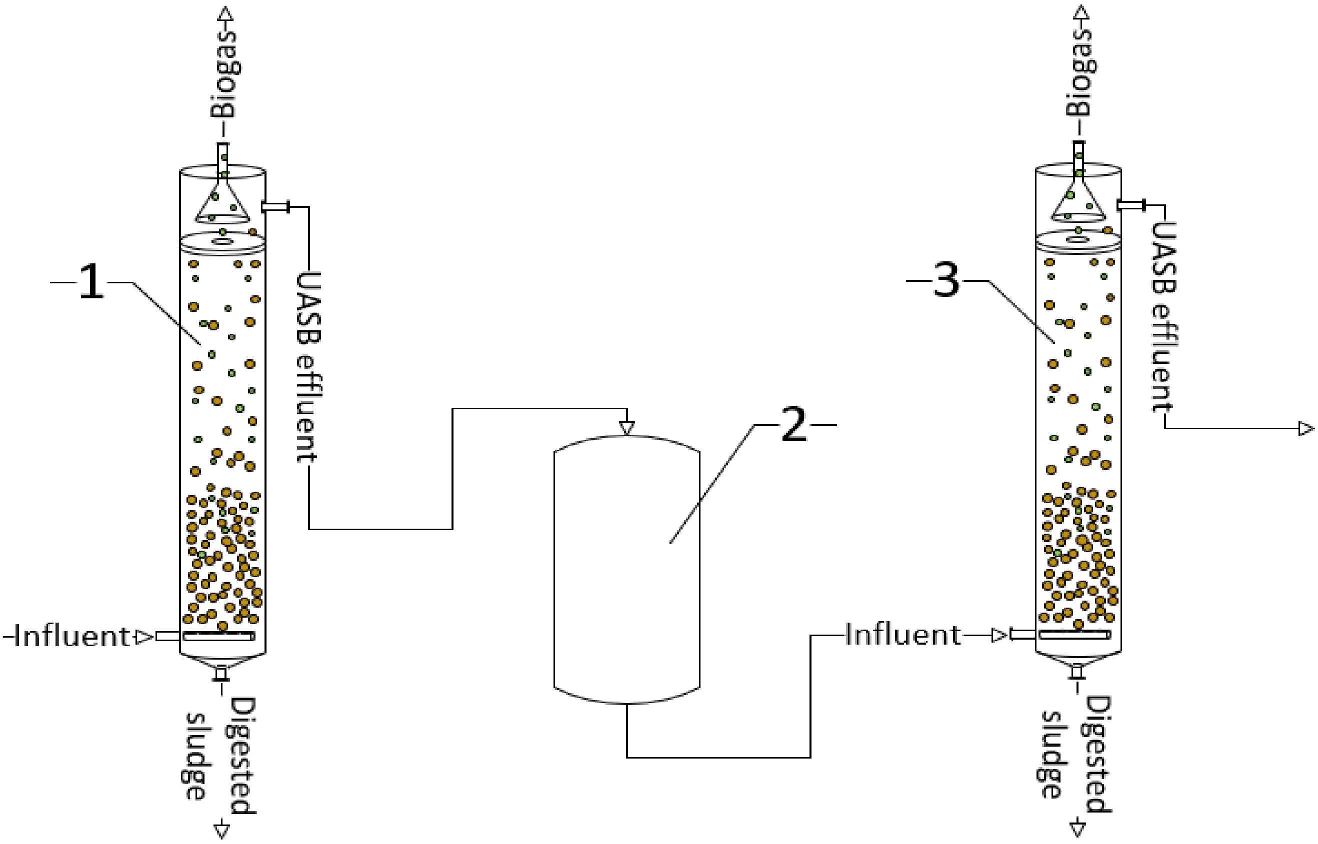


Figure 10. Simplified diagram of two-staged UASB system: (1) HUSB, (2) HUSB effluent tank, and (3) MUSB; based on [122].

The performance of the two-staged UASB system in relation to the various wastewater types is presented in the following table (Table 11). A high performance and stability of the AD process were achieved in a recent study concerning a two-staged UASB, in which ethanol wastewater was used for biogas production. A specific methane production yield of 11.83 m^3-$CH_4/m^3 \cdot d$ and COD removal higher than 90% was obtained at the optimal OLR of 32 $kg/m^3 \cdot d$ [123].

Some new research directions appear in relation to the two-staged UASB system. A recent study reports an improved methane yield and COD removal efficiency when supplementation with micronutrients such as Fe, Co, Cu, and Ni is carried out. As noted, the addition of 2 ppm of Co, Cu, and Ni and 50 ppm of Fe resulted in a 42.3% increase in the specific methane yield compared to the control [124].

Table 11. Some recent research related to the two-staged UASB process.

Feedstock	Influent COD, (g-COD/L)	Influent TN, (g/L)	COD Reduction (UASB-UASB), (%)	Methane Yield	OLR, (g-COD/L·d)	Operational Temperature of UASB, (°C)	Reference
Baker's yeast wastewater	20 ± 0.5	Nd	35.98	1.2 $^{(1)}$	2.2–13.7	35	[125]
Cassava wastewater	14.5	Nd	86.4	0.921 $^{(1)}$	30, 60, 90, 120 and 150	55	[126]
Ethanol wastewater	65.8 $^{(2)}$ $\pm$ 0.662 51.4 $^{(3)}$ $\pm$ 4	0.8 ± 0.035	92	0.492 $^{(4)}$	28	37	[123]
Cassava wastewater	19–22	Nd	93	0.115 $^{(4)}$	10, 20, 25 and 30	37	[127]

$^{(1)}$—as L-CH_4/g-$COD_{removed}$; $^{(2)}$—as total COD; $^{(3)}$—as settled COD; $^{(4)}$—m^3-CH_4/kg-$COD_{applied}$; Nd—no data.

5.5. UASB–Membrane Bioreactor (UASB-MBR)

In this hybrid system, a membrane bioreactor (MBR) using a membrane that is mainly made of materials such as polyvinylidene fluoride (PVDF), polyethene (PE), polyether sulfone (PES), and polyvinyl chloride (PVC) is applied, and the pore size can range from 0.01 μm to 0.1 μm [18]. An MBR performs an activated sludge process combined with microfiltration [128]. The MBR process can be carried out in a submerged (SMBR) or side stream (SSMBR) form. Regarding the CASP, an MBR replaces a secondary clarifier and disinfection unit, allowing the process to be operated in a single step [129]. The following figure (Figure 11) presents a simplified diagram of the UASB-MBR hybrid system with the two mentioned types of operation.

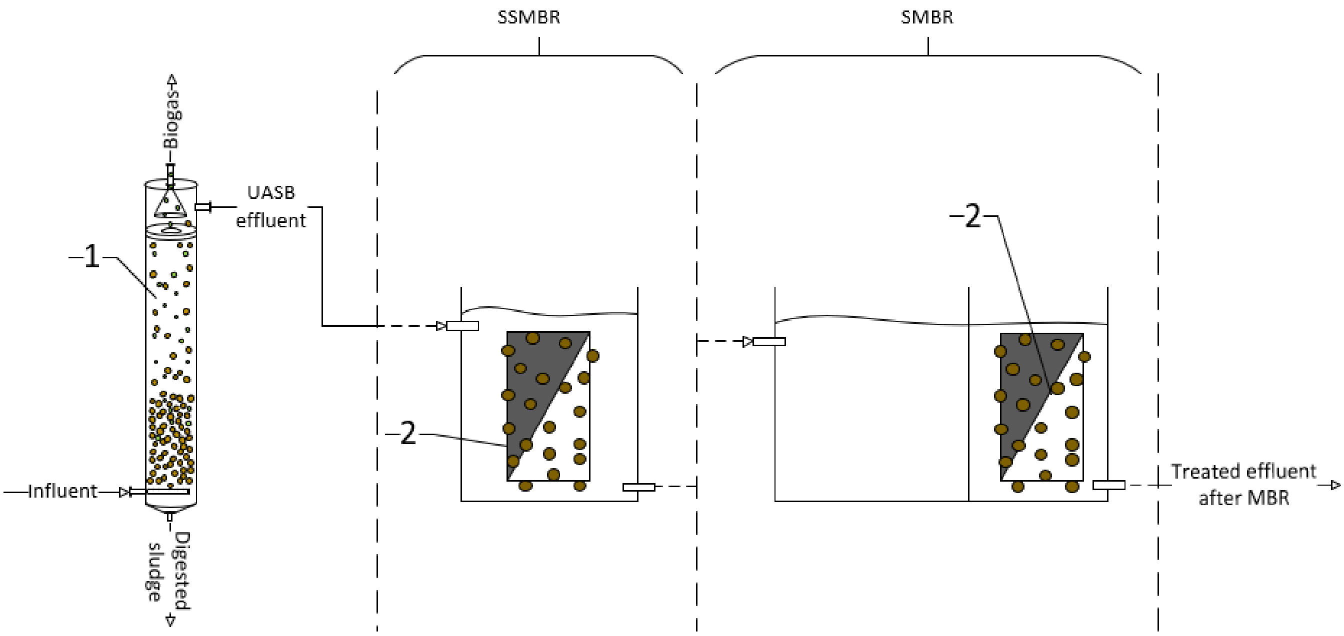


Figure 11. Simplified diagram of UASB-MBR hybrid system: (1) UASB and (2) membrane unit; based on [128,129].

The system provides good COD removal, as shown in some studies. For example, in [130], a COD removal of more than 90% was achieved when treating medium-strength seafood wastewater (0.5–3 g-COD/L) at an OLR of 6 g-COD/L·d. In another study examining the UASB-MBR system, a high tolerance to the OLR and operational temperature changes and high COD removal (soluble COD) of more than 95% were achieved when treating DW [131]. However, research that focuses UASB-MBR and standalone MBR treatments of DW are scarce. The following table (Table 12) provides examples of recent studies related to MBR coupled with UASB.

Table 12. Studies on UASB-MBR.

Feedstock	Influent COD, (g-COD/L)	COD Reduction (UASB-MBR), (%)	Methane Yield	OLR_{UASB}, (g-COD/L·d)	OLR_{MBR}, (g-COD/L·d)	Operational Temperature of UASB, (°C)	Reference
Semi-synthetic wastewater composed of diluted skimmed milk	1–2	99	182.6–299.3 $^{(1)}$	1.35–1.83	0.6–1.6	Nd	[131]
Berberine antibiotic wastewater	3.509 ± 0.125	98.7 ± 0.2	Nd	1.97–3.55	0.52–2.34	37 ± 1	[132]
Synthetic wastewater	1.054 ± 0.126	99 ± 2.1	0.30 ± 0.05 $^{(2)}$	Nd	Nd	37 ± 0.9	[133]

$^{(1)}$—as biogas yield expressed in L/kg-tCOD; $^{(2)}$—L-CH_4/g-$COD_{removed}$; Nd—no data.

Additionally, this hybrid system exhibits a good performance in removing micropollutants such as disinfectants, pharmaceuticals, detergents, pesticides, biocides, and hormone-active substances [129]. For example, in a study that examined the removal of carbamazepine, an antiepileptic drug, from low-strength municipal wastewater with a hybrid UASB-MBR (two-stage MBR) system, the removal efficiency of the pollutant was 38–48.9%, which is high (the commonly reported value for its removal with conventional biological treatment methods is less than 10%) [134].

Despite the promising results and performance, a few factors were identified that limit the implementation of MBR and its coupling with other treatment systems: high operational and capital costs, as well as membrane fouling and, hence, the necessity of frequent membrane substitutions [128]. However, membrane fouling has been extensively addressed in recent years. For example, [133] studied the effect of a novel UV photocatalytic quorum-quenching (GG) strategy with TiO_2-immobilized polymeric beads (p-QQ beads) to cope with membrane fouling. A significant decrease in transmembrane pressure, the primary cause of fouling, was observed with a high delay in membrane fouling. However, the membrane damage was still present.

5.6. UASB–Double Filtration (UASB-DF)

DF includes two filtration units, i.e., a direct upward filtration unit (medium gravel filter) and a downward quick filtration unit that works in series (Figure 12). The medium gravel filter is usually composed of several filtration layers (e.g., four) that vary in grain sizes. The downward quick filtration unit can constitute a single filtration layer with sand, the pore size of which can be within the range of 0.21 to 1.7 mm [119,135].

Compared to direct filtration, DF has advantages such as a higher filtration rate, better pathogen and faecal coliform removal efficiency, as well as the fact that after the first filtration unit, effluent is treated in the second one at the start of a filtration setting. DF is not often applied to treat effluent after anaerobic reactors, and some studies show that a proper reduction in pathogens is only achieved with this system. In contrast, organic and nutrient removals, in particular N-NH_4^+, still require the application of other methods. Therefore, some DF performance enhancement methods were proposed, including a preliminary coagulation/oxidation step and clinoptilolite application [101,135].

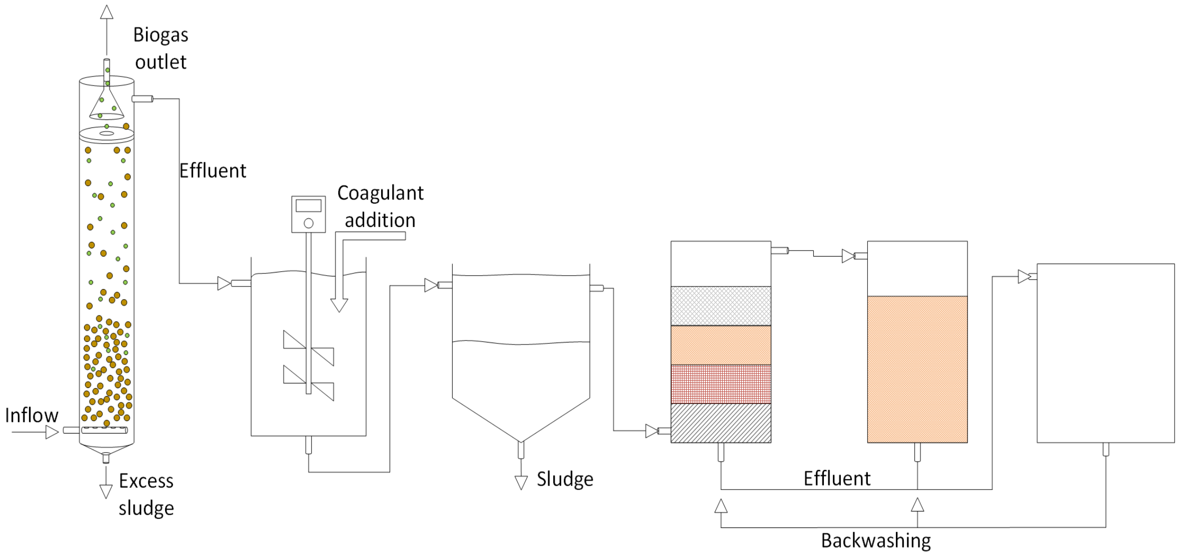


Figure 12. A typical process scheme of the UASB-DF system; based on [101,135].

5.7. Summary of the Pre-Treatment Approaches

Considering all the described pre-treatment approaches, the advantages and disadvantages of all the methods can be summarized (Table 13). However, regardless of the system used, there are several key issues that require further study. One of these is the removal of dissolved methane from the treated wastewater stream. The scale of the problem can be evidenced by the fact that it is estimated that in extreme cases, up to 50% of the produced methane can be discharged from UASB reactors along with the effluent. The scale of the described phenomenon depends primarily on the salinity of the effluent and its temperature. The release of such large amounts of methane with the effluent stream is not only an environmental problem (greenhouse gas emissions) but is also associated with a large loss of potentially useful energy. One of the most common solutions is membrane separation, but it requires further optimization in terms of membrane cleaning (fouling), process configuration, and process conditions. From the point of view of membrane processes, it is also important that the membranes receive wastewater that is free of sulphates and has a low organic pollutant load. In addition, unfortunately, most of these systems involve high transmembrane pressures, which translates into their high energy requirements, and often feature low liquid flow rates through the system. Other options for removing dissolved methane from effluents include oxidation of the effluent stream in a special reactor, the use of appropriately constructed biofilters or a downflow hanging sponge (DHS) reactor, or stripping and vacuuming. However, these are also associated with large energy inputs and low efficiency [136–138]. An interesting alternative for the removal of methane from wastewater streams may be hydraulic spray nozzles, which have demonstrated an efficiency of approximately 82% in removing methane from wastewater streams [136]. This does not change the fact that there is no universal solution. Further research is needed, considering the viability of solutions and safety aspects, especially since most of the reports in the literature are on a laboratory scale. We should also not forget about the potential operational problems associated with the operation of UASB reactors such as scum formation and crustation, odour nuisances, and GHG emissions. All of these can pose a major challenge in optimizing hybrid systems. Furthermore, the development of the described solutions requires further research, especially in terms of their environmental added value, where it is crucial to increase the number of analyses based on a life cycle assessment (LCA) and criterion indicators that are used in sustainability studies [53,139].

Table 13. Advantages and disadvantages of all mentioned effluent post-treatment approaches.

Pre-Treatment Approach	Advantages	Disadvantages
UASB–activated sludge (UASB-AS)	Excellent COD and nutrient removal efficiency (e.g., 67–97% COD reduction and 87–93% nutrient reduction)	Unsatisfactory total faecal coliform reduction; therefore, disinfection is required
UASB–sequencing batch reactor (UASB-SBR)	(1) Aeration tank and secondary clarifier are replaced with singular tank that works in cycles, which can be adjusted to work in aerobic, anaerobic, and anoxic conditions (2) Excellent COD, TC, and TP removals (3) Possibility of additional modifications, e.g., integration with OPG process	Low pathogen removal; aeration increases operating costs of wastewater treatment
UASB–biofilter (UASB-BF)	(1) Natural drought of air downstream provides aeration, and no excess sludge removal is necessary (2) Excellent COD and TN removal	Efficiency of nitrogen and phosphorus removal depends on wastewater; in some studies, efficiency was low
Two-staged UASB system (UASB-UASB)	(1) High performance and stability (2) High biogas yield	Possibility of accumulation of ammonia, which has a toxic effect on microorganisms; disrupts syntrophic connections between consortiums of microorganisms
UASB–Double Filtration (UASB-DF)	High filtration rate, better pathogen and faecal coliform removal efficiency, and after first filtration unit, effluent is treated in second one at start of filtration setting	Few publications, which makes it difficult to evaluate solution

6. Summary

This review article aimed to discuss the potential of joint stabilization of BW and DW. Both wastewater types are produced in large amounts and are characterized by high BOD_5 and COD values. A CASP can be insufficient to provide an efficient treatment and, instead, AD can be viewed as a good alternative. A high-rate anaerobic reactor, a UASB, is a well-studied technology, and the research interest, in particular in energy recovery as well as co-digestion, grows. The anaerobic co-digestion of wastewater streams from the brewing and dairy industries seems to be a good idea. There are several reasons for this: (1) they have a similar load of organic pollutants, so it will not significantly affect the hydraulic retention time of the wastewater in the reactor; (2) better dilution of toxic compounds (for example, wastewater from ice cream production is characterized by a high sulphur concentration, which is so high that it is toxic to methanogens); (3) potential synergistic effect that will allow for increased biogas production; and (4) improving the balance of macro- and microelements. However, assessing the feasibility of treating both wastewater streams in UASB reactors requires research. The first step is to define the most favourable share of wastewaters in the co-digestion mixture. In a further stage, the treatment process should be tested and optimized in continuous conditions in terms of operational parameters (HRT and OLR, among others), and the possibility of adapting the microorganisms and the structure of their population to changing environmental conditions should be studied. The issue of the amount of dissolved methane in the treated wastewater stream and the emissions of pollutants into the environment should also be looked into. The limitations of UASB reactors in terms of wastewater treatment also require the integration of reactors of this type with other solutions, because the effluent after the process requires additional post-treatment to meet the quality standard of wastewater treatment. This literature review mentioned and discussed some popular methods for effluent post-treatment, such as AS, SBR, BF, the two-staged UASB process, MBR, and DF.

UASB-AS is an old effluent post-treatment approach that can still provide a suitable treatment quality. UASB-SBR, a modification of the UASB-AS method, offers benefits such as lower area requirements and better removal efficiencies. An interesting method for effluent post-treatment after the AD process is the integration of a UASB-SBR with OPGs, which may lead to energy recovery and high-quality effluent treatment and a decrease in the operational costs of a WWTP because of the oxygen production. Mechanical aeration is, therefore, not required if such a method is applied.

The application of BF relies on packing media that support a consortium of microorganisms that degrade organic matter. This method can achieve good efficiency in terms of the COD and nutrient removals.

Applying MBR and DF for effluent post-treatment is an alternative to the biological methods. A membrane or filter media is used to separate the solid parts from the water. The efficiency of the COD and nutrient removal in this method is comparable with biological methods; however, in the case of DF, the pathogen and nitrogen removal can be low, so this is not frequently applied for post-effluent treatment.

Author Contributions: Conceptualization, G.S. and A.G.; methodology, G.S. and A.G.; software, G.S. and A.G.; validation, G.S. and A.G.; formal analysis, G.S. and A.G.; investigation, G.S. and A.G.; resources, G.S. and A.G.; data curation, G.S. and A.G.; writing—original draft preparation, G.S. and A.G.; writing—review and editing, G.S. and A.G.; visualization, G.S. and A.G.; supervision, G.S. and A.G.; project administration, G.S. and A.G.; funding acquisition, G.S. and A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the statute subvention of Czestochowa University of Technology (Faculty of Infrastructure and Environment).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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