COMPREHENSIVE ANALYSIS OF AEROBIC AND ANAEROBIC BIOLOGICAL TREATMENTS IN INDUSTRIAL WASTEWATER: MECHANISMS, ADVANTAGES, AND CRITICAL LIMITATIONS

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ABSTRACT

Biological treatments, including aerobic and anaerobic processes, are extensively applied in industrial wastewater management for effective pollutant removal and resource recovery. Aerobic systems offer high effluent quality but are energy-intensive, while anaerobic systems are more efficient for high-strength wastewater, enabling energy generation despite operational challenges such as long start-up periods, sensitivity to toxicants, pH instability, and odour issues. Hybrid systems offer a promising solution by integrating the strengths of both methods. Our review aims to bridge this gap by providing a comprehensive analysis of both approaches, specifically within the context of industrial wastewater management.

Keywords: *aerobic, aerobic granular sludge, anaerobic, biological treatment, conventional activated sludge, industrial wastewater*

INTRODUCTION

The rapid acceleration of urbanisation, industrialisation, and agricultural development has dramatically intensified global water demand, exacerbating pressures on water quality and ecosystem health [1]. The industrial sector accounts for roughly 22% of global water consumption, and approximately 80% of wastewater is released into aquatic systems, often containing high concentrations of pollutants [2]. These pollutants, while biodegradable, pose a significant threat to environmental stability, as concentrations of Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD) can reach extremely high levels, endangering both human health and aquatic life [3]-[5].

Consequently, wastewater treatment is essential for addressing these challenges. Treatment technologies are generally classified into physical, chemical, and biological processes [6]. Physical methods, including screening, sedimentation, flotation, and filtration, are typically employed in preliminary stages [7]. Chemical methods such as precipitation, coagulation, flocculation, chlorination, and oxidation further purify the water [7]. Biological treatments, particularly bioremediation and both aerobic and anaerobic processes play a central role in the degradation of organic pollutants. The selection of an appropriate treatment method depends on several factors, such as the treatment duration, system flexibility, budgetary constraints, and environmental impact [7]. Given these considerations, biological treatment has garnered increasing attention due to its sustainability, cost-effectiveness, and ability to degrade organic matter efficiently [8]. Additionally, biological treatment offers potential economic benefits under the Clean Development Mechanism (CDM), as methane gas produced during anaerobic digestion can be harnessed as a source of renewable energy, contributing to carbon credit earnings [9]-[10].

Biological treatment processes harness the natural metabolic activities of microorganisms to break down pollutants into simpler, less harmful compounds [11]. These processes are generally classified into aerobic and anaerobic systems. Aerobic treatment operates in the presence of oxygen, whereas anaerobic treatment functions in oxygen-deprived conditions, simultaneously producing biogas for energy and generating nutrient-rich digestate that can be utilised as fertiliser [12]. The effectiveness of biological treatment processes is influenced by factors such as temperature, pH, and substrate concentration, which can be optimized to improve both efficiency and stability [13].

While numerous studies have focused on either aerobic or anaerobic systems individually, there is a lack of comprehensive reviews addressing both approaches in parallel. Therefore, this paper aims to provide an in-depth analysis of the principles, advantages, limitations, and emerging trends in aerobic and anaerobic biological treatment methods for industrial wastewater in recent years.

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FUNDAMENTAL CONCEPTS OF AEROBIC SYSTEM

An aerobic wastewater treatment system is a biological process that uses microorganisms requiring oxygen to decompose organic matter into simpler compounds. These microorganisms metabolise organic pollutants through aerobic respiration, which can be described by Equation 1. This process results in the production of carbon dioxide, water, biomass and energy:

$$\text{Organic matter} + O_2 \rightarrow CO_2 + H_2O + \text{biomass} + \text{energy} \quad (1)$$

In addition to carbon removal, many aerobic systems facilitate nitrification, a two-step process where ammonia is converted to nitrate, as shown in Equations 2 and 3:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O + \text{energy} \quad (2)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- + \text{energy} \quad (3)$$

Oxygen is typically supplied through mechanical aerators or diffused air systems to maintain the necessary dissolved oxygen levels for microbial activity [6]. Aerobic systems can be divided into two main categories: suspended growth and attached growth processes [6].

Mechanism of Suspended Growth Process

In suspended growth processes, the microorganisms responsible for treatment are maintained in liquid suspension by appropriate mixing methods. These microorganisms form flocs that settle out during sedimentation, enabling the separation of treated water from sludge [2]. The sludge is either recycled to maintain the microbial population or wasted to control biomass levels in the system. A widely employed suspended growth process for wastewater treatment is the conventional activated sludge process [9],[14]-[15].

Conventional Activated Sludge (CAS)

The activated sludge process is a biological treatment unit that uses aerobic microorganisms suspended in wastewater to decompose organic pollutants and purify the wastewater [16]-[17]. In this approach, wastewater is combined with a microbial culture, referred to as activated sludge, in an oxygenated environment [18]. The microorganisms degrade organic matter, resulting in the formation of flocs, which can be readily separated from the treated water [6],[19]. An activated sludge treatment system consists of three primary elements: the aeration tank, the aeration system, and the secondary clarifier. A schematic representation of a CAS process is illustrated in Figure 1 to illustrate the key components and flow of the treatment system.

In the aeration tank, the influent wastewater is aerated with a population of aerobic microorganisms (activated sludge). This aeration can be achieved through either mechanical or diffused air systems [22]. Mechanical aerators use mixers on the surface of the water to agitate the contents of the aeration tank and to introduce dissolved oxygen into the mixed liquor. Conversely, a diffused air system uses blowers that push air through diffusers at the bottom of the aeration tanks. The oxygen transfer efficiency (OTE) improves with increasing depth as the bubbles remain in the water column for a longer duration and experience higher partial pressure [23]. Additionally, some aeration systems combine mechanical mixing with diffused air. Regardless of the type used, the primary function of an aeration system is to ensure effective oxygen transfer into the mixed liquor while maintaining thorough mixing within the aeration tank [22].

After aeration, the mixed liquor flows into the secondary clarifier. In this unit, activated sludge microorganisms are allowed to settle at the bottom while the clarified treated wastewater is discharged over the effluent weirs. Floc particles, typically ranging in size from 50 to 200 microns, are formed and settle in the clarifier, resulting in treated effluent with over 99% removal of suspended solids [24]. The settled microorganisms are then either returned to the aeration tank or disposed of as waste sludge [19]. The activated sludge is removed from the clarifier by means of the sludge collection mechanism that utilises pumps, an airlift, a differential head or a siphon mechanism [25]. It is essential for the operator to carefully control the amount of activated sludge returned and wasted from the clarifier, which depends on the hydraulic and organic loading of the system [26]. There are many types and modes of activated sludge systems, and each system is designed with specific operational parameters to meet diverse treatment objectives. Different systems have been studied at laboratory scale and full scale for different types of wastewater, as shown in Table 1.

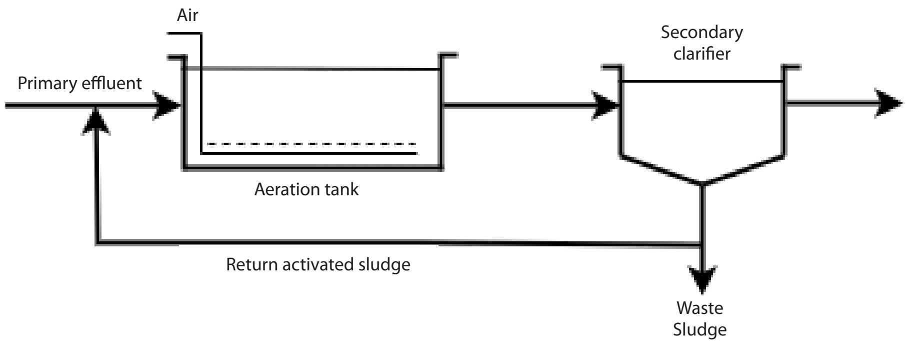


Figure 1 Schematic diagram of a CAS process
Adapted from: Rongxuan et al. [20], Sanderson et al. [21]

Table 1 Application of CAS in different industrial wastewater

Type of wastewater	Type of Reactor	pH	Temperature (°C)	OLR (kg COD/m^{3}d)	HRT (h)	Removal Efficiency (%)	Optimal Conditions	Reference
Industrial rubber wastewater	Stirred tank reactor	7.0	30 ± 2.0	1.0 - 3.0	72	COD: 83 - 96	OLR: 1.0–1.3 kg COD/m^{3}d	[27]
Food processing wastewater	-	7.8 ± 0.6	-	-	2.4 - 24	COD: > 90	HRT: 12h	[28]
Pharmaceutical wastewater	Batch single activated sludge process (BSASP)	7.0	25-35	-	10	Acetylsalicylic acid: 79.3	-	[29]
Textile-dyeing wastewater	Sequencing batch reactor	7.5 ± 1.1	30 ± 2.0	0.93	25	COD: 74.9 TN: 55	-	[30]
Cold pressed Zanthoxylum schinifolium oil wastewater	-	4.5 – 8.5	20 - 40	-	6 - 72	COD: 94.03 ± 0.31 TP: 93.33 ± 0.25 TN: 97.03 ± 0.26 Turbidity: 98.97 ± 0.02	Temperature: 30°C pH: 7.5 HRT: 48h	[31]

Note: OLR = Organic Loading Rate; HRT= Hydraulic Retention Time; COD= Chemical Oxygen Demand; TN= Total Nitrogen; TP= Total Phosphorus

Table 1 provides a comparative analysis of activated sludge system applications across various industrial wastewater sources. In the treatment of industrial rubber wastewater, a stirred tank reactor demonstrated high COD removal efficiencies ranging from 83% to 96%, particularly under optimised operating conditions with an organic loading rate (OLR) of 1.0–1.3 kg COD/m^3·d and a hydraulic retention time (HRT) of 72 hours. For food processing wastewater, COD removal efficiencies exceeding 90% were reported at an HRT of 24 hours. In the case of pharmaceutical wastewater, the application of a batch single activated sludge process (BSASP) effectively removed acetylsalicylic acid, achieving a removal efficiency of 79.3% at a temperature range of 25–35°C and an HRT of 10 hours. The treatment of textile-dyeing wastewater using a sequencing batch reactor (SBR) achieved COD and total nitrogen (TN) removal efficiencies of 74.9% and 55%, respectively, under an OLR of 0.93 kg COD/m^3·d and an HRT of 25 hours. Notably, the treatment of cold-pressed *Zanthoxylum schinifolium* oil wastewater yielded the highest performance, with COD and total phosphorus (TP) removal efficiencies of 94.05% and 93.33%, respectively, over a variable HRT of 6–72 hours. Optimal operating parameters included a temperature of 30°C and a pH of 7.5.

Aerobic Granular Sludge (AGS)

Key Metabolic Pathways of AGS System

In addition to activated sludge systems, the AGS system is another suspended growth process gaining increasing attention in wastewater treatment [32]. This system uses bio-granulation approaches to generate granular sludge with excellent settling properties and high biomass retention. Aerobic sludge granules are dense microbial aggregates comprising metabolically active microbial cells fixed in an extracellular polymeric substance (EPS) matrix [33] to promote the aerobic granulation process and improve the long-term stability of granules [34]. Generally, the AGS exhibits a layered structure. At the outer edges, it is in an oxygen-rich condition that allows the nitrifiers to fix, and when it goes deeper into the granule, oxygen starts depleting and anoxic or anaerobic condition is achieved in the middle where the denitrifier populations develop to perform the denitrification to convert nitrate to nitrogen gas [35]. This stratified structure of the aerobic granule and the associated biological processes is illustrated in Figure 2.

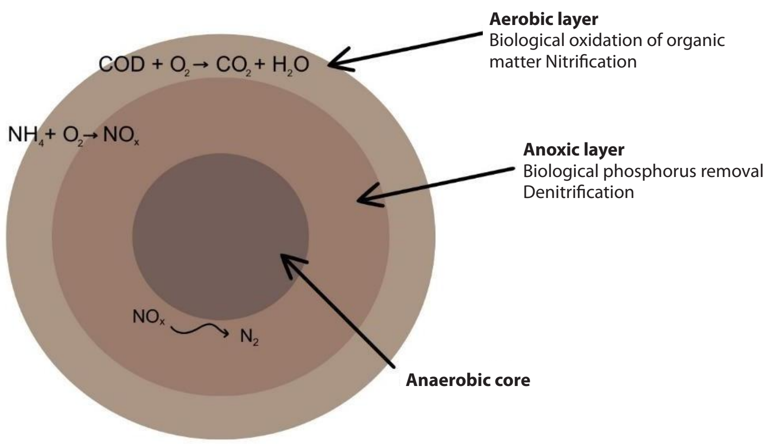


Figure 2 Schematic drawing of an aerobic granule with the different conversion processes for organic material, nitrogen, and phosphorus, taking place within the different redox zones. Adapted from: Britt-Marie Wilén et al. [36]

The granules have a complex, irregular structure rather than being perfectly spherical, featuring voids and channels that facilitate the deeper penetration of nutrients [33]. This structural complexity also contributes to process resilience; should bacteria on the granule's surface be lost, the inner microbial community can facilitate rapid recovery from disruptions. AGS develops from flocculent sludge under specific operating conditions, forming compact, self-sustaining granules [37]. While the precise mechanism of AGS formation remains a subject of ongoing research, it is understood to be a multi-step process influenced by a complex interplay of physical, chemical, and biological factors [36]. Consequently, a universally accepted explanation for the granulation process has yet to be established. Among the prevailing theories are the EPS hypothesis, the microbial self-aggregation hypothesis, and the four-step process model proposed by Yu Liu [38].

AGS is a promising technique for high-strength or highly toxic wastewater treatment [39]. These granular systems allow a more stable operation and the treatment of larger loads, remove multiple toxic pollutants, require smaller volumes for the settling systems and produce better quality effluents than the conventional systems [40]. AGS demonstrated various superiorities, including 1) high efficiency of solid-liquid separation; 2) strong tolerance to shock loading and toxicity; 3) integration of diverse microorganisms to achieve oxic and anoxic functions simultaneously in the microstructure; 4) high organic load rate (OLR), as AGS is more resistant to OLR impact than activated sludge [41]. These advantages make them suitable for simultaneous COD, nitrogen, and phosphate removal [34]. Accordingly, various wastewater treatment plants worldwide have implemented AGS technology. Examples include the Nereda system in Epe, Netherlands [42], and the Yancang wastewater treatment plant in Haining, China [43], which have significantly improved treatment efficiency and cost-effectiveness. Looking ahead, AGS technology is expected to become one of the mainstream methods in the field of wastewater treatment as this technology continues to mature and expand in its applications. Table 2 summarises the reports on biological nutrient removal in different types of wastewater.

Table 2 outlines a comparative summary of several studies evaluating the performance of aerobic granulation systems in treating various types of industrial and saline wastewater. The applications reviewed include industrial saline wastewater, shipboard slop wastewater, high-salinity wastewater, industrial wastewater containing ethylene glycol, and seawater-based wastewater. Overall, aerobic granulation demonstrated excellent pollutant removal efficiencies, particularly for COD, with removal rates ranging from 70% to over 99%, depending on the wastewater characteristics and operating conditions. Nitrogen removal was also substantial, with efficiencies between 30% and over 95%, indicating the system's strong potential for nutrient removal. In addition, high removal efficiencies were recorded for total petroleum hydrocarbons and total organic carbon (TOC), especially in shipboard slop and high-salinity wastewater, where removal exceeded 85% and 97%, respectively. Operating conditions varied among the studies, with pH values generally ranging from 6.2 to 8.0, temperatures between 4°C and 30°C, and hydraulic retention times (HRT) ranging from 6 to 24 hours. These findings underscore the robustness and versatility of aerobic granulation technology in effectively treating complex and high-strength wastewaters under diverse environmental conditions.

Benefits and Challenges of Suspended Growth Systems

Suspended growth systems serve as a cornerstone in modern wastewater treatment, with the CAS being the most historically significant and globally implemented biological treatment method. The CAS relies on a suspended microbial community—primarily floc-forming bacteria and protozoa—within an aeration tank to biologically degrade organic pollutants, nitrify ammonia, and, in some configurations, facilitate phosphorus removal. CAS demonstrate high treatment efficiency, capable of removing more than 90% of BOD, producing effluent BOD concentrations as low as 5 mg/L, and reducing TSS to 10 mg/L or below [7],[17]. In addition to its robust performance, the CAS process offers advantages such as ease of operation and moderate effectiveness in removing various pollutants, including COD. It has been extensively applied in both industrial and municipal wastewater treatment, consistently achieving high COD removal efficiencies under optimised conditions [7], [27]-[28]. However, the system remains highly energy- and sludge-intensive. Aeration alone can consume between 50% and 70% of a treatment plant's total energy, while sludge management can account for as much as

Table 2 A summary of different reports on pollutant removal by aerobic granulation systems

Wastewater Application	pH	Temperature	OLR (kg COD/m^3 d)	HRT(h)	Removal Efficiency (%)	Reference
Industrial saline wastewater	6.26 ± 0.85	-	1.5 ± 1.3	6	COD: 70 – 95 Nitrogen: 30 – 90	[44]
Industrial shipboard slop wastewater	7.78 ± 0.62	4	-	12	Total petroleum hydrocarbons: 87 – 97 TOC: 57-90	[45]
High salinity wastewater	7.5 – 8.0	25.0 ± 2.0	1.5	8.0	TOC:96.8- 97.8 TN:74.8- 85.3	[46]
Industrial wastewater containing ethylene glycol	-	30 ± 0.5	-	24	Ammonia nitrogen: ≥ 95 COD: ≥99.0	[47]
Seawater-based wastewater	-	25 ± 3	-	7.6	COD: 89 ± 3	[48]

Note: OLR = Organic Loading Rate; HRT= Hydraulic Retention Time; COD= Chemical Oxygen Demand; TN= Total Nitrogen; TP= Total Phosphorus; TOC= Total Organic Carbon

30% to 70% of overall operational costs [49]-[50]. In addition, the process generates substantial amounts of excess biomass, with up to 25%–50% of the influent COD being converted into waste sludge, requiring further handling and disposal [51].

In contrast, AGS systems represent a novel suspended growth approach that overcomes several limitations of CAS. AGS processes are typically carried out in sequencing batch reactors (SBRs), which promote the formation of compact, spherical microbial granules with a stratified internal structure. This configuration facilitates the simultaneous removal of organic carbon, nitrogen, and phosphorus within a single reactor, as the granules contain distinct aerobic, anoxic, and anaerobic zones [52]. AGS systems offer notable advantages in spatial efficiency, requiring up to 75% less reactor footprint compared to conventional systems. Additionally, they demonstrate superior solid-liquid separation performance, with high settling velocities ranging from 5 to 20 m/h and reduced settling times of approximately 5 to 10 minutes [53]. Additionally, AGS offers considerable energy savings. Studies have reported a 58–63% reduction in aeration energy usage and the complete elimination of return-activated sludge (RAS) pumping, contributing to overall operational efficiency [42],[54]. However, AGS presents several challenges, including a prolonged start-up period and sensitivity to operational parameters such as Sludge Retention Time (SRT), HRT, shear force, and organic loading [33],[55]. Moreover, achieving full granulation can be difficult—up to 30% of the biomass may remain in floc form under certain conditions [39],[56]. AGS also performs better with higher-strength wastewater and may require bioaugmentation, feast-famine regimes, or shear optimisation for stability [57].

Despite these limitations, AGS is promising for future applications, particularly where land availability is constrained, and energy efficiency is a priority. Meanwhile, CAS continues to serve as a robust and reliable baseline technology for a wide range of treatment scenarios. The choice between CAS and AGS depends on factors such as influent characteristics, site constraints, operational capabilities, and sustainability goals. A comparative summary of the key advantages and limitations of the CAS and AGS systems is featured in Table 3 to provide a clearer understanding of their respective performances and operational considerations.

MECHANISM OF ATTACHED GROWTH SYSTEMS

In attached growth processes, the microorganisms responsible for the conversion of organic material or nutrients are attached to an inert packing material, also known as a biofilm [58]. For attached growth processes, the substrate is consumed within a biofilm where the biofilm acts as the primary site for microbial activity, and the treated effluent separates naturally as it passes through the system. Packing materials used in attached growth processes include rock, gravel, sand, and a wide range of plastic and other synthetic materials [59]. The packing can be submerged completely in liquid or partially submerged, with air or gas space above the biofilm liquid layer [60]. Depending on the growth conditions and the hydrodynamics of the system, the biofilm thickness may range from 100 mm to 10 mm [61]. The various types of attached growth systems are outlined in Table 4.

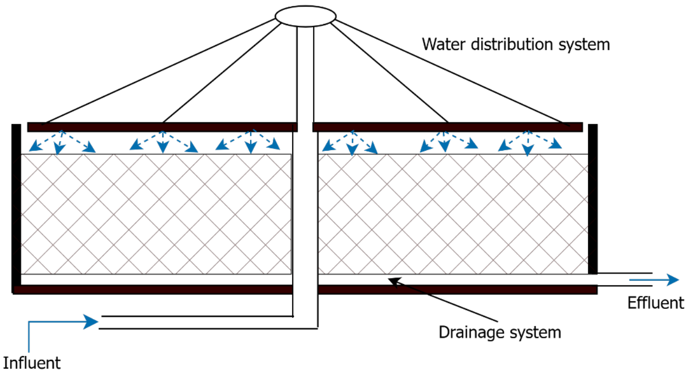
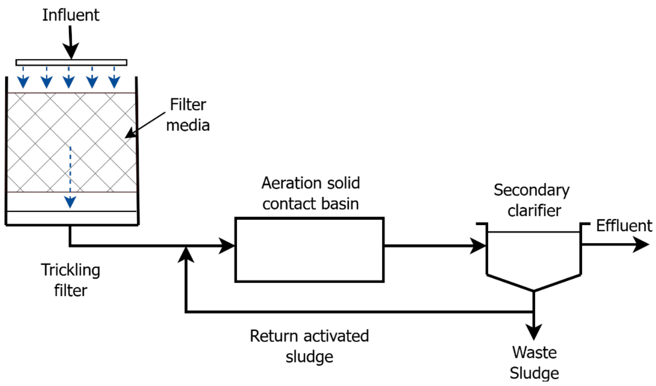
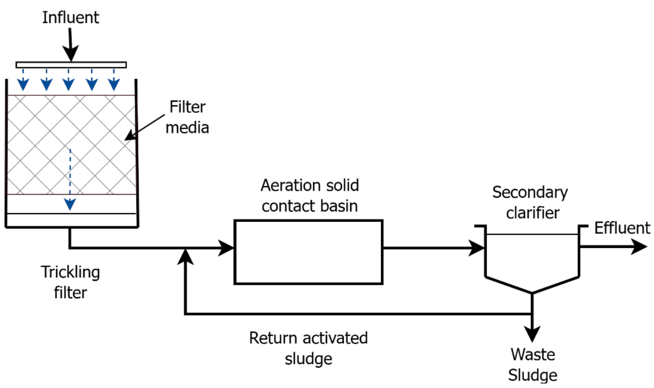
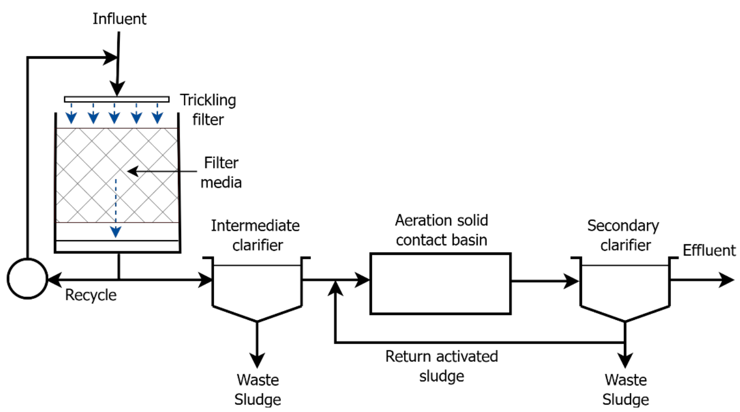
Benefits and Challenges of the Attached Growth Treatment System

Attached growth systems exhibit several advantages, notably their low sludge production, which mitigates the challenges associated with sludge handling and disposal [59]. Furthermore, attached growth systems exhibit enhanced resistance to toxic materials compared to suspended growth systems. This is attributed to

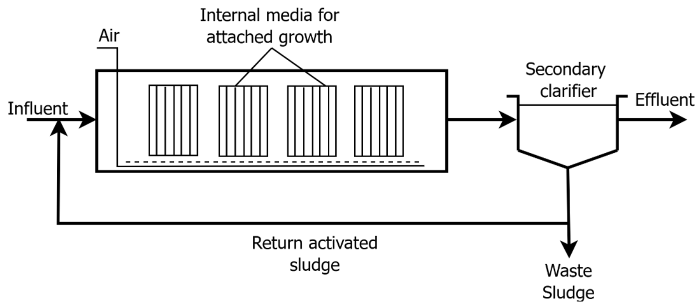
Table 3 Comparative analysis of CAS and AGS systems in wastewater treatment

Aspects	CAS	AGS
Mechanism	Suspended microbial flocs (mainly bacteria and protozoa) in a continuous flow aeration tank [7],[17]	Dense, spherical microbial granules in SBRs with aerobic, anoxic, and anaerobic zones [52]
Sludge Production	High sludge yield: up to 25–50% of influent COD converted to biomass [51]	Reduced sludge production; better settleability [53]
Energy Consumption	Aeration accounts for 50–70% of total energy use [49]	58–63% lower aeration energy use; no RAS pumping needed [42],[54]
Operational Footprint	Requires a large land area and reactor volume [7]	Reduces footprint by up to 75% [53]
Solid-Liquid Separation	Moderate settling; longer settling time [7]	High settling velocity (5–20 m/h) and short settling time (5–10 min) [53]
Ease of Operation	Simple to operate and manage; widely implemented [7]	Sensitive to SRT, HRT, shear force, and organic loading; requires skilled operation [55]
Start-Up Time	Relatively short and well established [17]	Longer start-up; incomplete granulation (up to 30% floc) under certain conditions [39],[122]
Sludge Management Cost	Accounts for 30–70% of operational costs [49]-[50]	Lower excess sludge reduces sludge handling needs [53]
Suitability	Effective for a wide range of industrial and municipal influents [28]	Better suited for high-strength wastewater; may require bioaugmentation or feast-famine regimes [57]
Technology Maturity	Mature, globally implemented technology [7]	Emerging and innovative; limited large-scale implementation [52]
Sustainability Considerations	High energy use and sludge production pose sustainability challenges [49]-[50]	Lower energy demand, compact footprint, and enhanced nutrient removal support sustainable treatment goals [42],[53]-[54]

Table 4 Different types of attached growth systems [60],[62]-[64]

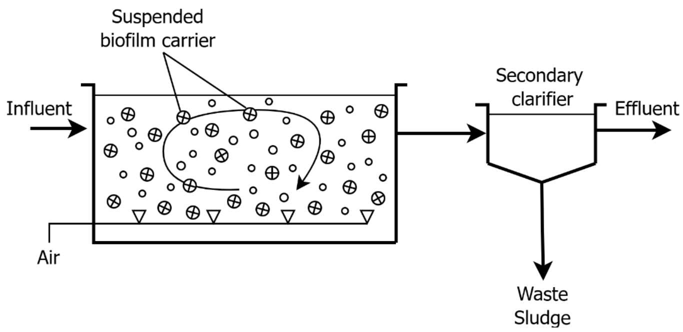
Type of system	Characteristics
Trickling filter 	1. Wastewater is sprinkled over the filter filled with non-submerged packing material or biofilm. 2. Biofilm (slime layer or zoogleal film) supports microbial growth. 3. Soluble substrates and oxygen diffuse into the biofilm, promoting biomass growth. 4. Colloidal and particulate materials are removed through attachment and trapping. 5. Detached solids were removed in a secondary clarifier. 6. Clarifier underflow solids are not recycled to the filter.
Sequential Combined Processes 	Trickling Filter/Solids Contact (TF/SC): 1. Low-loaded trickling filter followed by an aerated solids contact tank and secondary clarification. 2. Trickling filter removes most soluble BOD. 3. Solids contact tank promotes bioflocculation of colloids and particulates, further reducing soluble BOD.
	Trickling Filter/Activated Sludge (TF/AS): 1. High-loaded trickling filter removes 40–70% of BOD as a roughing filter. 2. Activated sludge process completes the treatment to achieve final effluent quality. 3. Suitable for high-strength wastewater treatment due to low energy use per quantity of BOD removed. 4. Produces good SVI values in activated sludge mixed liquor. 5. Commonly used for industrial wastewater treatment.
	Series TF/AS Process: 1. Trickling filter followed by an activated sludge process, with an intermediate clarifier in between. 2. Intermediate clarifiers reduce solids loading and optimize aeration requirements. 3. Used for system upgrades, treating industrial and domestic wastewater together, or protecting activated sludge systems from toxic compounds.

Integrated Fixed-Film Activated Sludge (IFAS)



1. Combines biofilm media with activated sludge systems for wastewater treatment.
2. Biofilm carriers (polymeric or sponge-like materials) increase biomass concentration, enhancing nitrification and treatment capacity.
3. Media kept suspended using air sparging or mixing, and screens prevent media loss.
4. Regular maintenance prevents excessive biofilm accumulation.
5. Used with polymer floating or fixed media to improve treatment performance

Moving-Bed Biofilm Reactor (MBBR)



1. Similar to IFAS, but does not use return-activated sludge.
2. Suspended biofilm carriers occupy up to 70% of the reactor volume, providing surface area for microbial growth.
3. Often integrated with granular media or membrane filtration for enhanced effluent quality.

the formation of a biofilm by the microorganisms on the media surface, providing a protective barrier. The biofilm structure allows microorganisms deeper inside to be shielded from the toxic effects of harmful substances while only the outer layer is exposed [65]. Additionally, it facilitates the removal of high amounts of nutrients and supports simultaneous nitrification and denitrification on both the exterior and interior surfaces of the biofilm, making it versatile for various treatment applications. The utilisation of carrier media increases the biomass within the system, enabling higher loading rates and shorter HRT without necessitating an increase in tank volume [66]. Given these notable advantages, attached growth systems have found widespread application in diverse sectors, including the treatment of textile wastewater [67], industrial effluents [68], and phenol-ammonia wastewater [69]. Accordingly, this system has demonstrated a high COD, phenol and nitrogen removal capacity, validating their effectiveness.

Despite its many advantages, the attached growth process has certain limitations. One significant drawback is ponding, especially for trickling filters. Ponding can happen when there is too much growth or a large amount of suspended material in the incoming wastewater [70]. It occurs when the media particles stick together or the spaces between them become blocked. This is more of an issue with rock filters, particularly those with smaller rocks. Ponding can cause uneven air and water flow in the filter, leading to poor treatment results, the growth of mosquitoes, and unpleasant odours. [71]. Another challenge is the need for a high dissolved oxygen concentration in biofilm. This is because IFAS and MBBR operate at elevated DO concentrations to achieve effective denitrification [71]. This can increase operational complexity and costs. These disadvantages highlight the need for careful design and management to optimise the performance of the attached growth process in wastewater treatment.

From a commercialisation perspective, attached growth treatment systems such as Trickling Filters, IFAS, and MBBR have already demonstrated successful large-scale implementation in municipal and industrial wastewater treatment facilities. They are practical for retrofitting existing plants or creating new treatment infrastructures with limited footprints due to their modular design, scalability, and comparatively simple operation. Because of their high treatment efficiency, low sludge production, and shock load resilience, MBBR and IFAS technologies are widely used and commercially available from various global manufacturers [62],[72]-[73]. Furthermore, by incorporating carrier media into traditional systems, it is possible to increase biomass retention and shorten HRT, which appeals to industries with time and space constraints. However, factors like the initial cost of carrier materials, the energy needed for aeration, and the requirement for constant media maintenance all affect the viability of commercial deployment. Overall, attached growth systems are technically and economically viable for industries seeking robust and sustainable wastewater solutions.

FUNDAMENTAL CONCEPTS OF ANAEROBIC SYSTEM

Anaerobic digestion is a biological process that decomposes complex organic materials into methane (CH_4), carbon dioxide (CO_2), and water through four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The process occurs under

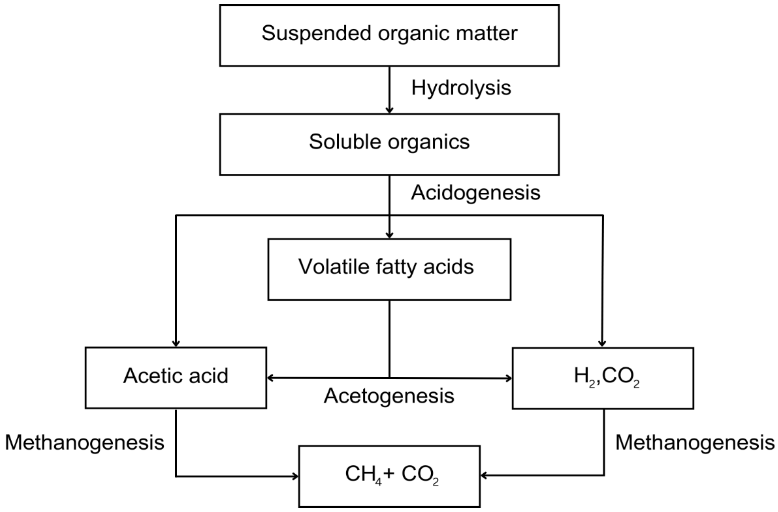


Figure 3 Process of anaerobic decomposition of organic matter [74]

strict conditions without oxygen and relies on a coordinated microbial community. Figure 3 outlines the process of anaerobic decomposition of organic matter.

During hydrolysis, hydrolytic bacteria break down insoluble organic materials and high molecular weight compounds, such as carbohydrates, lipids, proteins, and nucleic acids, into soluble substances like amino acids, sugars, and fatty acids. Acidogenesis follows, where acidogenic bacteria ferment these products into volatile fatty acids (VFAs), ammonia (NH_3), CO_2, hydrogen (H_2), and other by-products. In acetogenesis, acetogenic bacteria convert VFAs and alcohols into acetic acid, along with additional CO_2 and H_2. Finally, methanogenic bacteria transform acetic acid, H_2, and CO_2 into CH_4 and CO_2, completing the process [74]. Figure 4 illustrates the processes that happen in an anaerobic digester, while Table 5 presents an overview of various aerobic digestion technologies currently employed in the industry.

To ensure efficient treatment in environments without oxygen, several factors like pH, alkalinity, temperature, solids retention time (SRT), and HRT must be carefully considered. Maintaining the right pH balance is crucial, as methanogenic bacteria, responsible for methane production, are sensitive to extreme pH levels and perform best in the range of 6.8–7.2 [76], while acid-producing bacteria can tolerate a wider range of 4.0–8.5 [77]. High organic loading rates (OLR) can lead to volatile fatty acid (VFA) buildup, inhibiting methanogenesis and destabilising the system [78]. Alkalinity acts as a buffer to prevent pH fluctuations, with an optimal level of 70 meq $CaCO_3$/L required for stability [74]. Temperature also plays a key role in anaerobic digestion. Methanogenic bacteria thrive under mesophilic conditions (20–42°C), particularly at 35–37°C, where greater microbial diversity and stability are observed compared to thermophilic conditions (50–60°C) [79]. While higher temperatures can enhance biogas production and pathogen destruction, they

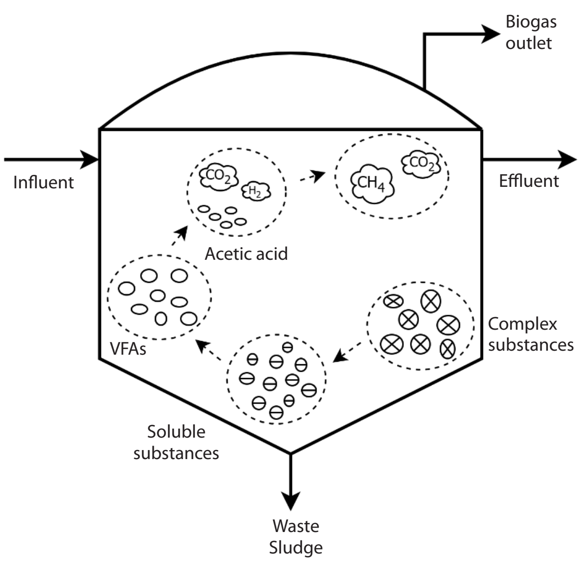


Figure 4 The process of anaerobic digestion in a reactor. Adapted from: Ying Zang et al. [75]

Table 5 Different anaerobic treatment process technologies for wastewater [9],[60]

Treatment Process	Characteristics
Upflow Anaerobic Sludge Blanket (UASB)	1. Upflow reactor with granular anaerobic biomass. 2. Reactor heights: 5-20 m. 3. Gas-liquid-solid separator for separating solids and biogas collection.
Expanded Granular Sludge Blanket (EGSB)	1. Modified UASB with higher upflow velocity (4-10 m/h) and greater height. 2. Reactor heights up to 25 m. 3. Designed for soluble substrates. COD loading up to 35 kg/m^3·d. 4. It is not as efficient as UASB for particulate solids capture.
Internal Circulation UASB (IC)	1. Two stacked UASB reactors with high recirculation and upflow velocities (8-20 times higher than UASB). 2. Reactor heights up to 25 m. 3. More efficient overall COD removal. 4. Second stage for improved effluent solids and biomass capture.
Fluidised Bed (FB)	1. Uses dense anaerobic biomass on inert particles (0.1-0.3 mm). 2. Upflow velocities: 10-20 m/h. 3. Applicable for soluble wastes or small particulates. 4. 25-300% bed expansion in fluidised mode.
Anaerobic Contact Process (ANCP)	1. Completely mixed reactor with suspended biomass, solids recycle. SRT > HRT. 2. Includes degassing, mixing, and liquid-solids separation chambers.
Anaerobic Filter (ANF)	1. Unmixed reactor with fixed film anaerobic biomass. 2. Available in upflow (ANFU) and downflow (ANFD) configurations.
Anaerobic Hybrid Process (AnHYB)	1. Combines UASB and ANF. 2. High biomass concentration and volumetric organic removal in the lower UASB section. 3. Upper filter captures suspended solids and removes VFAs.
Anaerobic Membrane Process (AnMBR)	1. A mixed reactor system with suspended biomass and a synthetic membrane is used for solids-liquid separation. 2. Long SRT with short HRT.
Anaerobic Baffled Reactor (ABR)	1. A series of upflow reactors with sludge rise and fall with gas production. 2. Limitations include restricted studies on pilot or lab scale.
Anaerobic Migrating Blanket Reactor (AMBR)	1. Similar to ABR but includes mechanical mixing and sludge blanket retention without settlers. 2. Influent feed can be shifted.

also increase free ammonia concentrations and promote the growth of hydrogen scavengers, which can outcompete methanogens and lead to system failure [80]-[81].

Furthermore, temperature drops below 35°C reduce bacterial activity significantly, slowing digestion and growth [76]. Although hydrolysis and acidogenesis are less susceptible to temperature fluctuations, acetogenesis and methanogenesis, especially in substrates rich in ammonium, urea, and protein, are significantly influenced by temperature due to their reliance on temperature-sensitive bacterial populations. The increased production of free ammonia in these substrates further exacerbates this temperature sensitivity [82]. Table 6 presents a comparative summary of commonly used anaerobic reactors, outlining their pros and cons based on recent literature, while Table 7 presents a summary of the application of different anaerobic systems for diverse industrial wastewater streams.

Benefits and Challenges of Anaerobic Treatment Systems

A major benefit of anaerobic digestion is its significantly lower biomass yield. Anaerobic processes produce about 6 to 8 times less biomass compared to aerobic processes [60]. This reduction in sludge production not only minimises the environmental burden but also significantly reduces the costs associated with sludge processing and disposal, which are major concerns in aerobic treatment. Additionally, anaerobic processes are capable of handling higher volumetric organic loadings compared to aerobic processes and provide high stability in response to influent fluctuations [101]. Large-scale anaerobic reactors can handle OLRs ranging from 20 to 40 kg COD/m^3 d, while lab-scale reactors have demonstrated the ability to sustain much higher OLRs, reaching 86 to 306 kg COD/m^3 d [102]. This highlights the significant potential for advancing anaerobic digestion technologies. Furthermore, anaerobic digestion produces biogas, a valuable renewable energy source, eliminating the need for external energy inputs [103]. In this context, adding supplements like enzymes, nanomaterials, pH buffers, nutrients, and bio-augmentation materials can boost biogas production and methane yield [77]. These enhancements not only improve the efficiency of the anaerobic process but also contribute to a more sustainable and cost-effective energy recovery system.

Despite its advantages, anaerobic digestion comes with several limitations. One significant concern is its longer start-up time, which can take months compared to the few days required for aerobic processes [76]. Anaerobic systems are also more sensitive to toxic compounds such as phenol and require careful operational stability [104]. Moreover, there is a potential need for alkalinity addition to maintain stable pH levels. Anaerobic systems may

Table 6 A summary of the advantages and disadvantages of anaerobic reactor technologies

Reactor Type	Advantages	Disadvantages	Reference
UASB	1. Treats a wide range of high-strength industrial wastewaters (e.g., food, dairy, distillery, pharmaceuticals) 2. High removal performance 3. Simple construction 4. Low CAPEX/OPEX 5. Small footprint	1. Long start-up time (up to 8 months) 2. Sludge washout 3. Low methane yields and inefficient COD removal under some conditions 4. Corrosion, toxicity, odour 5. Instability at low temperatures 6. Needs secondary treatment	[83]-[85]
EGSB	1. High tolerance to toxic compounds at high concentrations 2. High loading capacity (up to 45 kg COD/m^3·d) 3. Compact design with high upflow velocity 4. Longer contact time between wastewater and biomass 5. Treats wastewater with higher loading rates and lower HRTs than UASB	1. Sensitive to suspended solids (SS) 2. SS accumulation affects granule formation and reactor performance 3. Best suited for SS-free wastewater, like corn alcohol or cheese whey wastewater	[83],[86]-[87]
Internal Circulation Reactor (IC UASB)	1. Enhanced mass transfer 2. Higher tolerance to OLR 3. Shorter start-up time 4. High COD removal, gas production, and OLR tolerance 5. Smaller footprint 6. Better shock load resilience	1. Poor biogas generation during start-up can cause inadequate mixing and low mass transfer efficiency 2. Limited studies for high-concentration refractory wastewater	[88]-[89]
Fluidised Bed Reactor	1. Reduced clogging and short-circuiting 2. Shallow footprint 3. Prevents biomass loss	1. Operation is complex and empirical 2. Modeling and optimization are challenging 3. Limited studies on performance parameters	[90]
Anaerobic Membrane Bioreactor (AnMBR)	1. Combines anaerobic digestion and membrane filtration 2. High biomass retention and stability 3. Superior pollutant removal 4. 49% more biogas recovery than conventional AD 5. Suitable for SS-containing wastewater (e.g., dairy, distillery) 6. CO_2 emissions significantly reduced	1. High installation, operational, and maintenance cost 2. Membrane fouling issues (e.g., reduced flux, increased pressure)	[86],[91]-[92]
ABR	1. Less cell migration 2. Reduced short-circuiting 3. Handles shock loads and degrades recalcitrant substances	1. Complex mechanical mixing setup needed to prevent clogging and ensure uniform feed	[83]
AMBR	1. High loading capacity 2. Short HRT and simple design 3. Constant flow operation	1. Lower heavy metal removal efficiency compared to UASB	[93]

require alkalinity concentrations of 2000 to 3000 mg/L as $CaCO_3$ due to the high gas-phase CO_2 concentration [60]. Other challenges include the potential for odour production due to the production of hydrogen sulphide, the corrosive nature of digester gas, and the need for skilled operational expertise to maintain the balance between volatile fatty acid production and methanogenic activity. Proper process design and control of feed, temperature, and pH can help manage these issues [76]. Lastly, anaerobic processes may result in effluent with high BOD levels due to residual VFAs and dispersed solids. As a result, further treatment, typically through aerobic polishing, is often necessary to achieve the desired effluent quality. The combination of anaerobic and aerobic processes, either in series reactors or integrated single-tank systems, has proven effective for industrial wastewater treatment in both temperate and warmer climates [105]-[107]. This approach reduces energy needs and sludge production while utilising the strengths of both systems [108].

CURRENT APPLICATION AND CASE STUDIES

Case Study 1: Kloten–Opfikon WWTP, Switzerland

An actual example of the application of advanced AGS technology in the treatment of industrial and municipal wastewater is the Kloten–Opfikon Wastewater Treatment Plant (WWTP) in Switzerland. In addition to treating wastewater from industrial sources like the Zurich airport, which frequently contains different concentrations of pollutants and nutrients, this facility also treats wastewater from two municipalities. The Kloten–Opfikon WWTP utilizes a sequencing batch reactor (SBR) system that is designed to treat an average flow of 10,227 ± 2735 m^3/day, equivalent to the wastewater produced by a population of 44,000. Before entering the biological treatment phase, the wastewater undergoes primary clarification, with a HRT of 2.3 hours, to allow the removal of large solids. The use of AGS in the biological treatment step has greatly improved treatment efficiency by providing better solid-liquid separation, reducing sludge volume, and lowering operational costs associated with sludge disposal [109].

Table 7 A summary of different applications of anaerobic system

Type of wastewater	Type of Treatment	pH	Temperature (°C)	OLR (kg COD/m^{3}d)	HRT (h)	Removal efficiency (%)	Reference
N, N-dimethylformamide-containing industrial wastewater	UASB	-	36 ± 2	1.6-3.3	6-48	COD: 98.55 ± 0.3	[94]
Mature leachate	EGSB	8.47 ± 0.10	35 ± 1	0.9-23.6	44-120	COD: 80	[95]
Corn alcohol wastewater	IC	4.2-7.2	30 ± 1 35 ± 1	12.46	38.4-115.2	COD: > 98	[88]
Raw municipal water	FB	-	20 ± 1	-	-	COD: 82	[96]
Synthetic wastewater	ANF	6.8-7.6	25	-	2	COD: 90	[97]
Seafood processing wastewater	AnMBR	5.5-8.0	-	1.2-3.6	8-24	COD: 61.04	[98]
High concentration allicin wastewater	ABR	6.5-7.5	30 ± 2	-	6-24	COD: 97.45	[99]
Raw composting leachate	AMBR - anaerobic sludge bed reactor	7.55	35	1.8-19.7	120-240	Heavy metals: 76.47-94.50	[93]
Protein-rich wastewater	Anaerobic Sequencing Batch Reactor (ANSBR)	6.8-7.8	36 ± 0.5	0.8-4.2	19.2-108	COD: 90	[100]

Note: OLR = Organic Loading Rate; Hydraulic Retention Time; COD=Chemical Oxygen Demand

Case Study 2: Central Cervecera de Colombia Wastewater Treatment Plant

The Central Cervecera de Colombia (CCC) wastewater treatment plant, located in Sesquilé, north of Bogotá, is used to treat high-strength brewery effluent. By using anaerobic digestion technology, specifically the BIOTIM® UASB system, the CCC plant processes 2,400 m^3 of wastewater per day. This industrial wastewater treatment facility effectively handles the variable organic loads typical of brewery operations while producing biogas captured and utilised in the brewery's boilers. The anaerobic treatment technology is supplied by Waterleau, a specialised water treatment company, and has helped the brewery achieve both environmental compliance and sustainability goals by converting waste into energy. The implementation demonstrates the effectiveness of anaerobic treatment for high-strength industrial wastewater in the food and beverage sector [110].

Path Forward

Despite the significant evolution of aerobic and anaerobic biological treatment technologies, several challenges continue to hinder their optimal performance and large-scale adoption in industrial wastewater treatment. Aerobic systems, though effective in pollutant removal, are burdened by high energy demands due to continuous aeration requirements. Additionally, excessive biomass generation necessitates frequent sludge handling, increasing both operational complexity and cost.

To address these limitations, intermittent aeration (IA) has emerged as a promising strategy. IA alternates between aerated and non-aerated phases, thereby enhancing denitrification efficiency while reducing energy consumption. Francesco Bianco et al. [111] reported that IA can cut energy use by up to 50% and increase total nitrogen (TN) removal by 72%. This operational flexibility supports a more sustainable treatment approach, balancing performance and efficiency [112-114].

Excess sludge production remains another critical bottleneck. Traditional disposal methods contribute significantly to the environmental and operational footprint of wastewater treatment plants (WWTPs). Biological alternatives such as the Oxic-Settling-Anaerobic (OSA) process have shown promise, with the potential to reduce sludge production by up to 60% without chemical or thermal pre-treatment [115]. The OSA approach utilizes alternating oxic and anaerobic conditions in a side-stream reactor to stimulate microbial decay and improve sludge stability, potentially allowing for beneficial reuse [115]-[117].

Another key innovation is the implementation of off-gas analysis systems for real-time monitoring of OTE. This technique allows for precise aeration control, supporting energy optimisation and greenhouse gas mitigation. The Charneca de Óbidos WWTP demonstrated that off-gas tools could significantly reduce emissions and operational energy [39]. Incorporating these systems into facilities with complex tank configurations could greatly enhance energy efficiency and operational control [39].

AGS systems offer further advantages, including smaller reactor footprints, improved settling characteristics, and enhanced nutrient removal. However, limitations such as long start-up periods and granule instability under variable loading conditions impede their full-scale implementation. Future studies should focus on rapid granulation methods using seeding materials or biofilm carriers, as well as on real-time monitoring systems to enhance system resilience.

To support this, recent research by Hadeer Abdalla et al. [118] introduced AI-driven optimisation models for AGS systems. A hybrid model integrating artificial neural networks and random forests (ANN-RF) with response surface methodology (RSM) on six AGS batch reactors showed that the RSM-AI model achieved 99.1% COD removal at optimal COD:N (35–145), COD:P (145–355) ratios, and 7.6 h HRT, outperforming fuzzy logic-genetic algorithm (96.8% at 6.0 h HRT).

This integrated approach supports AGS scale-up and offers a path toward smarter, sustainable wastewater treatment.

On the anaerobic front, widespread application is constrained by long start-up times, sensitivity to toxic compounds, and the need for post-treatment to address incomplete organic removal. Additionally, the accumulation of ammonia and VFAs often compromises process stability. Enhancing anaerobic performance may be possible through the incorporation of acidic and alkaline pre-treatment, membrane filtration, nanomaterial additives, and bioaugmentation strategies [9],[86].

A particularly promising advancement is the integration of Anaerobic Digestion with Partial Nitritation/Anammox (AD-PN/A). AD is well-established for its ability to treat high-strength wastewater with energy recovery and reduced sludge production, especially for COD concentrations above 1,000 mg/L. The PN/A process offers a more sustainable solution than conventional nitrification/denitrification, as it is carbon-free, reduces aeration energy by up to 62.5%, and minimises sludge production by 90% [119]. This integrated system has demonstrated high nitrogen removal efficiencies, lower greenhouse gas emissions, and significant cost savings across various sectors, including printing and dyeing [120], landfill leachate [121], and pharmaceuticals [9].

Looking ahead, the convergence of hybrid treatment systems, machine learning-based monitoring, and automated process control is expected to redefine the landscape of industrial wastewater treatment. Emphasis should also shift toward resource recovery, including the reclamation of clean water, nutrients, and biogas, aligning WWTPs with circular economy principles. Achieving this transition from lab-scale innovation to full-scale implementation will require coordinated efforts in microbial engineering, pilot-scale demonstrations, and regulatory reforms to encourage sustainable adoption.

CONCLUSION

This review highlights the principles, applications, and challenges of aerobic and anaerobic biological treatment systems for industrial wastewater. Aerobic processes like activated sludge and aerobic granular sludge (AGS) are efficient at removing organic pollutants and nutrients but require high energy and generate large sludge volumes. Anaerobic systems, such as the Upflow Anaerobic Sludge Blanket (UASB) reactor, are suitable for high-strength wastewater, producing less sludge and valuable biogas. However, they face challenges like long start-up times and the potential need for post-treatment. Integrating aerobic and anaerobic methods into hybrid systems offers a balanced approach, enhancing treatment efficiency and sustainability. These technologies support circular economy principles by enabling resource recovery and reducing waste, contributing to several United Nations Sustainable Development Goals, including clean water and sanitation, affordable and clean energy, responsible consumption and production as well as climate action. Advancing these systems demands continued research into innovative materials, microbial optimisation, and improved designs to overcome limitations and promote environmental sustainability and global development.

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REFERENCES

[1] M.O.F. Shaikh A. Razzak, Z. Alsheikh, L. Alsheikhmohamad, D. Alkuroud, A. Alfayez, S.M. Zakir Hossain, and M.M. Hossain, “A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater,” *Environmental Advances,* vol. 7, 2022.

[2] S.A. Deblina Dutta and S. Kumar, “Industrial wastewater treatment: Current trends, bottlenecks, and best practices,” *Chemosphere,* vol. 285, 2021.

[3] Q.Q. Cai, B.C.Y. Lee, S.L. Ong, and J.Y. Hu, “Fluidize d-b e d Fenton technologies for recalcitrant industrial wastewater treatment–Recent advances, challenges and perspective,” *Water Research,* vol. 190, 2021.

[4] M.F.C. Y.J. Chan, C.L. Law, and D.G. Hassell, “A review on anaerobic–aerobic treatment of industrial and municipal wastewater,” *Chemical Engineering Journal,* vol. 155, 2009.

[5] “Wastewater Report 2018,” The International Water Association, 2018.

[6] S.K. Saurabh Yadav, “Progress on the Development of Techniques to Remove Contaminants from Wastewater: A Review,” *Applied Science and Engineering Progress,* vol. 16, no. 3, 2023.

[7] P.S.K.A. Saravanan, S. Jeevanantham, S. Karishma, B. Tajsabreen, P.R. Yaashikaa and B. Reshma “Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development,” *Chemosphere,* vol. 280, 2021.

[8] M.V.A. Rengasamy Sathya, N.A. Al-Dhabi, P. Vijayaraghavan, S. Ilavenil ,and T.S. Rejiniemon “Towards sustainable wastewater treatment by biological methods – A challenges and advantages of recent technologies,” *Urban Climate,* vol. 47, 2023.

[9] C.S. Zixuan Deng, G. Ma, X. Zhang, H. Guo, T. Zhang, Y. Zhang, Y. Hu, D. Li, Y. Y. Li, and Z. Kong, “Anaerobic treatment of nitrogenous industrial organic wastewater by carbon–neutral processes integrated with anaerobic digestion and partial nitritation/anammox: Critical review of current

advances and future directions," *Bioresource Technology,* vol. 415, 2025.

[10] N.E.Z. Ignacio Durruty, and Jorge F. Gonza´lez, "Kinetic studies on the anaerobic degradation of soluble and particulate matter in potato wastewater," *Biosystems Engineering,* vol. 111, 2012.

[11] T.M.A. Motasem Y.D. Alazaiza, M.B. Ramu, S.S. Abu Amr, Mohammed F.M. Abushammala and D.E. Nassani, "Global perspectives on industrial wastewater management: A bibliometric analysis of research output," *Journal of Hazardous Materials Advances,* vol. 17, 2025.

[12] K.A. Milan Malhotra, L. Pisharody, A. Singh, J. Rajesh Banu, S.K. Bhatia, S. Varjani, S. Kumar, C.G. Fern´andez, S. Kumar, R. Singh, and V. K. Tyagi, "Biorefinery of anaerobic digestate in a circular bioeconomy: Opportunities, challenges and perspectives," *Renewable and Sustainable Energy Reviews,* vol. 166, 2022.

[13] P.C.A. Ernest Mbamalu Ezeh and E. Aworabhi, "Biological Treatment Techniques for Sewage: Aerobic and Anaerobic Processes," in *Sewage - Management and Treatment Techniques*, H. A. Hasan Ed., 2024.

[14] M.B.M.M. Ghangrekar, "3.5 - Suspended Growth Treatment Processes," *Comprehensive Water Quality and Purification,* vol. 3, pp. 74-89, 2014.

[15] A.C. Paulo Marcelo Bosco Mofatto, D.D. Trapani, and G. Mannina, "Investigation of intermittent aeration and oxic settling anaerobic process combination for nitrogen removal and sewage sludge reduction," *Chemosphere,* vol. 363, 2024.

[16] M.M. Mathew, K. Kathana, V. Vats, R. Dhanker, R. Kumar, H.U. Dahms, and J.S. Hwang, "Biological Approaches Integrating Algae and Bacteria for the Degradation of Wastewater Contaminants—A Review," 2022.

[17] N. Horan, "Suspended growth processes," *Handbook of Water and Wastewater Microbiology,* pp. 351-360, 2003.

[18] L.W.Y. Song, X. Qiang, W. Gu, Z. Ma, and G. Wang, "An overview of biological mechanisms and strategies for treating wastewater from printing and dyeing processes," *Journal of Water Process Engineering,* vol. 55, 2023.

[19] F. P. Oskar Modin, B. M. Wilen, and M. Hermansson, "Nonoxidative removal of organics in the activated sludge process," *Critical Reviews in Environmental Science and Technology,* vol. 46, 2016.

[20] M.A.R. Wang, S. Tsuji, H. Hara-Yamamura, A. Hata, B. Zhao, M. Ihara, and R. Honda, "Removal performance of SARS-CoV-2 in wastewater treatment by membrane bioreactor, anaerobic-anoxic-oxic, and conventional activated sludge processes," *Science of the Total Environment,* vol. 851, 2022.

[21] H.A. Sanderson, C. Fricker, R.S. Brown, and A. Majury, "Antibiotic resistance genes as an emerging environmental contaminant," *Environmental Reviews,* vol. 24, 2016.

[22] H.J.C. Keffala, F. Zouhir, G. Jmii, A. Mokhtar, M.N. Dine Liady, and B. Tychon, "Effect of biomass concentration in membrane bioreactor design on alpha factor for two large pilot systems: Case study of mechanical surface aeration and air insufflation system," *Desalination and Water Treatment,* 2024.

[23] J.A.L.-B. Baquero-Rodríguez, D. Nolasco, and D. Rosso, "A Critical Review of the Factors Affecting Modeling Oxygen Transfer by Fine-Pore Diffusers in Activated Sludge," Water Environ Res., 2018.

[24] L. Metcalf, *American Sewerage Practice: Disposal of Sewage*, vol. 3. New York, NY, USA: McGraw-Hill Book Company, Inc., 1935.

[25] M. Sustarsic, "Wastewater Treatment: Understanding the Activated Sludge Process," *Chemical Engineering Progress,* vol. 105, 2009.

[26] D. Kinnear, "Return activated sludge flow rate control strategies," *Proc. Water Environ. Fed.*, 2004.

[27] W.S. Krainara, B. Suraraksa, P. Prommeenate, P. Thayanukul, and E. Luepromchai, "Bioaugmentation of activated sludge with the immobilized 2-mercaptobenzothiazole-degrading bacterial consortium for rubber industrial wastewater treatment," *Journal of Water Process Engineering,* 2023.

[28] H.V.P. Duan, H. Tsukamoto, T. Hori, and A. Terada, "Microaerophilic activated sludge system for ammonia retention from high-strength nitrogenous wastewater: Biokinetics and mathematical modeling," *Biochemical Engineering Journal,* vol. 191, 2023.

[29] R.S. Ali, H. M. Ali, H. Gadallah, E.S. Mansor, H. Abdallah, M. Shalaby, and A. M. Shaban "Integrated system of anoxic / activated sludge and ultrafiltration membrane for zero liquid discharge of pharmaceutical industrial wastewater treatment," *Journal of Environmental Chemical Engineering,* vol. 11, no. 1, 2023.

[30] T.G. Pan, H. Liao, Z. Huang, Z. Qian, F. Li, and J. Li, "Adding iron shavings in activated sludge system to enhance removal of refractory organics and nitrogen for textile-dyeing wastewater," *Journal of Environmental Chemical Engineering,* vol. 11, 2023.

[31] P.H. Zhou, C. Ma, X. Peng, M. Fu, T. Ren, and J. Kan, "Treatment of cold pressed Zanthoxylum schinifolium oil wastewater: Process, sludge characteristics, and microbial

diversity analysis using biochemical methods," *Journal of Environmental Management,* vol. 377, 2025.

[32] A.R. Hamza, F.-Z. Ezzahraoui, G. Morgan, and O. T. Iorhemen, "A review of the state of development of aerobic granular sludge technology over the last 20 years: Full-scale applications and resource recovery," *Case Studies in Chemical and Environmental Engineering,* vol. 5, 2022.

[33] Y. Liu and J.-H. Tay, "State of the art of biogranulation technology for wastewater treatment," *Biotechnol. Adv.*, vol. 22, no. 7, pp. 533–563, 2004.

[34] X. K. Liu, X. Li, and Y. Yuan, "Performance of aerobic granular sludge in a sequencing batch bioreactor for slaughterhouse wastewater treatment," *Bioresource Technology,* vol. 190, 2015.

[35] G.R.V. Vydehi, G. Shyamala, S.B.G., V. Nagaraju, M. Mekala, and R. R. Karri, "Aerobic granular sludge-based sustainable wastewater treatment: Process, bottlenecks, and knowledge gap through scientometric perspective," *Journal of Hazardous Materials Advances,* vol. 16, 2024.

[36] R.L. Wilén, F. Persson, O. Modin, and M. Hermansson, "The mechanisms of granulation of activated sludge in wastewater treatment, its optimization, and impact on effluent quality," *Applied Microbiology and Biotechnology,* vol. 102, pp. 5005-5020, 2018.

[37] M.Z. Liu, G.T. Daigger, J. Huang, and G. Song, "Granule formation mechanism, key influencing factors, and resource recycling in aerobic granular sludge (AGS) wastewater treatment: A review," *Journal of Environmental Management* vol. 338, 2023.

[38] J.-H.T. Yu Liu, "The essential role of hydrodynamic shear force in the formation of biofilm and granular sludge," *Water Research,* vol. 36, 2002.

[39] I.V. a.-R. Torre and R. Kahhat, "Integrating microplastic management into a broader wastewater decision-making framework. Is activated granular sludge (AGS) a game changer?," *Journal of Water Process Engineering,* vol. 69, 2025.

[40] D.-J.L. Adava, J.-Y. Laib, " Treating chemical industries influent using aerobic granular sludge: Recent development," *Journal of the Taiwan Institute of Chemical Engineers,* 2009.

[41] L.F. Wan, Z. Li, X. Liu, L. Lin, and C. Wu, "Formation, application, and storage-reactivation of aerobic granular sludge: A review," *Journal of Environmental Management,* 2022.

[42] M.K. d. K.M. Pronk, B. de Bruin, P. Kamminga, R. Kleerebezem, and M.C.M. van Loosdrecht, "Full scale performance of the aerobic granular sludge process for sewage treatment," *Water Research,* vol. 84, pp. 207-217, 2015.

[43] L.-B. D. Li, A. Cai, G.-X. Huang, and H. Horn, "Aerobic Sludge Granulation in a Full-Scale Sequencing Batch Reactor," *BioMed Research International,* vol. 2014, no. 1, 2014.

[44] T.C.-D.P. Carrera, C.M. Castro-Barros, R. M´endez, A. Val del Río, and A. Mosquera-Corral, "Features of aerobic granular sludge formation treating fluctuating industrial saline wastewater at pilot scale," *Journal of Environmental Management,* vol. 296, 2021.

[45] A.V. Campo, G. Rabbeni, W. Arancio, G. Gallo, and G. Di Bella, "Reactivation of aerobic granular sludge for the treatment of industrial shipboard slop wastewater: Effects of long-term storage on granules structure, biofilm activity and microbial community," *Journal of Water Process Engineering,* vol. 42, 2021.

[46] S.W. Zhang, S. Lin, Y. Miao, D.-H. Kim, B. Xu, W. Du, X. Shi, and S. Huang, "Aerobic granular sludge inoculant for enhancing high salinity wastewater treatment: Performance and value-added biopolymer recovery," *Chemical Engineering Journal,* vol. 498, 2024.

[47] Z.L. Qi, C. Zhang, X. Tan, C. Wan, X. Liu, L. Wang, and D.-J. Lee "Biodegradation of real industrial wastewater containing ethylene glycol by using aerobic granular sludge in a continuous-flow reactor: Performance and resistance mechanism," *Biochemical Engineering Journal,* 2020.

[48] A.S.M. Miranda, M. E. Tiritan, P. M. L. Castro, and C. L. Amorim "Microbiome adaptation of aerobic granular sludge allows process resilience during the treatment of seawater-based wastewater with pharmaceutica," *Journal of Water Process Engineering,* vol. 72, 2025.

[49] M.L. Zhou, B. Chen, L. Sun, and H. Lu, "Microbubble- and nanobubble-aeration for upgrading conventional activated sludge process: A review," *Bioresource Technology,* vol. 362, 2022.

[50] N.Z. Haiping Yuan "Progress of improving waste activated sludge dewaterability: Influence factors, conditioning technologies and implications and perspectives," *Science of the Total Environment,* vol. 912, 2024.

[51] L.L. Kong, Y. Xue, M. Yang, and Y.-Y. Li "Challenges and prospects for the anaerobic treatment of chemical-industrial organic wastewater: A review," *Journal of Cleaner Production,* vol. 231, 2019.

[52] Y.V. Nancharaiah and G.K.K. Reddy, "Aerobic granular sludge technology: Mechanisms of granulation and biotechnological applications," *Bioresource Technology,* vol. 247, 2018.

[53] J.R.V. Grisales Penagos and M. Villarraga Manrique, "Formulation of a protocol to evaluate the aerobic

granulation potential (AGP) of an inoculum," *MethodsX,* vol. 9, 2022.

[54] V. N. Yarlagadda, S. Nancharaiah, and T. V. Mohan, "Aerobic granular sludge: The future of wastewater treatment," *Curr. Sci*., vol. 117, no. 3, pp. 395–404, 2019, doi: 10.18520/cs/v117/i3/395-404.

[55] A.R.M.B. Rollemberg, P.I.M. Firmino, and A.B. dos Santos, "Aerobic granular sludge: Cultivation parameters and removal mechanisms," *Bioresource Technology,* vol. 270, pp. 678-688, 2018.

[56] R.M. Lin, Y. Hu, J. Lin, S. Sun, J. Jiang, T. Li, Q. Liao and J. Luo, "Reviewing bottlenecks in aerobic granular sludge technology: Slow granulation and low granular stability," *Environmental Pollution,* vol. 263, 2020.

[57] L.L. Liu, W. Ye, B. Zhao, Y. Peng, G. Liu, X. Gao, and X. Pen "Simultaneous nitrification and denitrification in a hybrid activated sludge-membrane aerated biofilm reactor (H-MABR) for nitrogen removal from low COD/N interflow: A pilot-scale study," *Journal of Environmental Management,* vol. 367, 2024.

[58] S. Waqas, M. R. Bilad, Z. Man, Y. Wibisono, J. Jaafar, T. M. I. Mahlia, A. L. Khan, and M. Aslam, "Recent progress in integrated fixed-film activated sludge process for wastewater treatment: A review," *J. Environ. Manage*., vol. 268, p. 110718, 2020, doi: 10.1016/j.jenvman.2020.110718.

[59] N. M. Eskandari Payandeh and P. Dadgar, "Study of Biological Methods in Landfill Leachate Treatment," *Open Journal of Ecology,* 2017.

[60] M. Eddy, *Wastewater Engineering Treatment and Resource Recovery, Fifth Edition*. McGraw-Hill Education, 2014.

[61] WEF, *Aerobic Fixed-Growth Reactors: A Special Publication*. Alexandria, VA, USA: Water Environment Federation, 2000.

[62] E.K. Themeli, P. Kaperonis, S. Michalaki, D. Mamais, C. Noutsopoulos, and S. Malamis, "Development of an integrated fixed-film activated sludge (IFAS) reactor treating landfill leachate for the biological nitrogen removal through nitritation-denitritation," *Journal of Environmental Management,* vol. 365, 2024.

[63] P.A. Zishan Aslam, R. Islam, A.H. Khan, H. Samaraweera, A. Hussain, and T.I. Zargar, "Recent developments in moving bed biofilm reactor (MBBR) for the treatment of phenolic wastewater -A review," *Journal of the Taiwan Institute of Chemical Engineers,* vol. 166, 2025.

[64] M.G. Kevin Maciejewski, B. Kim, P. Michel, and R. Gourdon, "Effect of trickling filter on carbon and nitrogen removal in vertical flow treatment wetlands: A full-scale investigation," *Journal of Environmental Management,* vol. 303, 2022.

[65] C. Nicolella, M.C.M. van Loosdrecht, and J.J. Heijnen "Wastewater treatment with particulate biofilm reactors," *Journal of Biotechnology,* vol. 80, 2000.

[66] T. Sriwiriyarat and C. W. Randall, "Performance of IFAS wastewater treatment processes for biological phosphorus removal," *Water Res.*, vol. 39, no. 16, pp. 3873–3884, 2005.

[67] A.H. Shuralla, A.M. Hirue, and G. D. Gebreeyessus. "Treatment appraisal and fate of HMs in up-flow anaerobic sludge blanket and trickling filter-based sewage treatment process: The case of a kaliti Centralized Wastewater Treatment Plant, Addis Ababa, Ethiopia," *Heliyon,* vol. 10, 2024.

[68] A.A. Mina Dolatshah, F. Gholami, and S. Nazari., "Development and modeling of an integrated fixed-film activated sludge (IFAS) system for simultaneous nitrogen and carbon removal from an industrial estate wastewater," *Biotechnology Reports,* vol. 41, 2024.

[69] R.K.S. Ganesh Swain, B.S. Giri, R.S. Singh, Ravi P. Jaiswal and B.N. Rai, "Collective removal of phenol and ammonia in a moving bed biofilm reactor using modified bio-carriers: Process optimization and kinetic study," *Bioresource Technology,* vol. 306, 2020.

[70] L.R.-M. Aaron A. Forbis-Stokes, and M.A. Deshusses "Nitrifying trickling filters and denitrifying bioreactors for nitrogen management of high-strength anaerobic digestion effluent," *Chemosphere,* vol. 204, 2018.

[71] E. Metcalf, "Chapter 9: Attached Growth and Combined Biological Treatment Processes," in *Wastewater Engineering Treatment and Resource Recovery, Fifth Edition*, 2014.

[72] Y.Z. Zihua Lan, R. Liang, Z. Wang, J. Sun, X. Lu, Y. He, and Y. Wang, "Comprehensive comparison of integrated fixed-film activated sludge (IFAS) and AAO activated sludge methods: Influence of different operational parameters," *Chemosphere,* vol. 357, 2024.

[73] A.M. Duduku Saidulu and A.K. Gupta, "A systematic review of moving bed biofilm reactor, membrane bioreactor, and moving bed membrane bioreactor for wastewater treatment: Comparison of research trends, removal mechanisms, and performance," *Journal of Environmental Chemical Engineering,* vol. 9, 2021.

[74] J.B. Lise Appels, J. Degre`ve, and R. Dewil, "Principles and potential of the anaerobic digestion of waste-activated sludge," *Progress in Energy and Combustion Science,* 2008.

[75] Y.Y. Ying Zang, Y. Hu, H.H. Ngo, X.C. Wang, and Y.Y. Li, "Zero-valent iron enhanced anaerobic digestion of pre-

concentrated domestic wastewater for bioenergy recovery: Characteristics and mechanisms," *Bioresource Technology,* vol. 310, 2020.

[76] M.B.K.V. Rajeshwari, A. Kansal and K. Lata, V.V.N. Kishore, "State-of-the-art of anaerobic digestion technology for industrial wastewater treatment," *Renewable and Sustainable Energy Reviews,* 2000.

[77] F.L.K. Ahmed Elsayed, A. Marcus, A. AlSayed, M.S. Zagloul, C. Muller, K.Y. Bell, D. Santoro, J. Norton, and E. Elbeshbishy, "Application of additives for anaerobic digestion intensification: A comprehensive review on improving biogas production and methane yield," *Applied Energy,* vol. 381, 2025.

[78] Z. Zhao, Y. Zhang, S. Chen, and Q. Yu, "Bioelectrochemical enhancement of anaerobic methanogenesis for high organic load rate wastewater treatment in a up-flow anaerobic sludge blanket (UASB) reactor," *Sci. Rep.*, vol. 4, p. 6658, 2014, doi: 10.1038/srep06658.

[79] D. Karakashev, D. J. Batstone, and I. Angelidaki, "Influence of environmental conditions on methanogenic compositions in anaerobic biogas reactors," *Appl. Environ. Microbiol.*, vol. 71, no. 1, pp. 331–338, 2005.

[80] A.C.-K. Magdalena Zielin´ska, M. Zielin´ski, and M. De˛bowski, "Impact of temperature, microwave radiation and organic loading rate on methanogenic community and biogas production during fermentation of dairy wastewater," *Bioresource Technology,* vol. 129, 2013.

[81] M. Goberna, M. Gadermaier, C. García, B. Wett, and H. Insam, "Adaptation of methanogenic communities to the cofermentation of cattle excreta and olive mill wastes at 37°C and 55°C," *Appl. Environ. Microbiol.*, vol. 76, 2010, doi: 10.1128/AEM.00961-10.

[82] W.W. Huiban He, Y. Wang, H. He, P. Zhang, H. Wang, W. Zhu, Y. Zhao, Z. Cui, and X. Yuan, "Combined effect of temperature and total solid content on methane yield: Balancing hydrolysis and methanogenesis," *Fuel,* vol. 381, 2025.

[83] Y.Y. Kuan-Yeow Show, H. Yao, H. Guo, T. Li, D.-Y. Show, J.-S. Chang, and D.-J. Lee, "Anaerobic granulation: A review of granulation hypotheses, bioreactor designs and emerging green applications," *Bioresource Technology,* vol. 300, 2020.

[84] S.G. Mohamad Abdallah, C.F. Webster, M. Harb, H. Beyenal, and M. Wazne, "Enhancement of the start-up and performance of an upflow anaerobic sludge blanket (UASB) reactor using electrochemically-enriched biofilm," *Enzyme and Microbial Technology,* vol. 188, 2025.

[85] A.M. Abeer El Shahawy, S. EL-Shatoury, D. Ahmed, A. Aboulfotoh, A. Dohdoh, and H. L. Gough, "Using phragmites australis biochar bio-augmented with actinomycetes for enhancing UASB reactor performance: A field study," *Journal of Water Process Engineering,* vol. 68, 2024.

[86] Y.F. Xinzheng Zhang, T. Hao, R. Chen, T. Zhang, Y. Hu, D. Li, Y. Pan, Y. Y. Li, and Z. Kong, "Insights into current bio-processes and future perspectives of carbon-neutral treatment of industrial organic wastewater: A critical review," *Environmental Research,* vol. 241, 2024.

[87] C.A. Philipp Witkabel, "A systematic literature review of microbial anammox consortia in UASB/ EGSB-reactors," *Chemosphere,* vol. 367, 2024.

[88] G.X. Junlin Ji, H. Yang, J. Liu, C. Wang, F. Yin, W. Zhang, and S. Hao, "Study on the treatment of corn alcohol wastewater by the internal circulation anaerobic reactor," *Water Science & Technology,* vol. 88, 2023.

[89] L.X.Z.K.M. Wang, K.F. Ji, S.N. Xu, and J.D. Wang, "Evaluation of a modified internal circulation (MIC) anaerobic reactor for real antibiotic pharmaceutical wastewater treatment: Process performance, microbial community and antibiotic resistance genes evolutions," *Journal of Water Process Engineering,* vol. 48, 2022.

[90] N.S. Shaikh Abdur Razzak, S.M. Zakir Hossain, M. Muhitur Rahman, Y. Yuan, M. Mozahar Hossain, and J. Zhu, "Hybrid machine learning modeling of nitrogen removal from wastewater using gas-liquid-solid circulating fluidized bed riser," *Chemical Engineering Research and Design,* vol. 207, 2024.

[91] W.A. Salahaldin M.A. Abuabdou, N. Choon Aun, and M.J.K. Bashir, "A review of anaerobic membrane bioreactors (AnMBR) for the treatment of highly contaminated landfill leachate and biogas production: Effectiveness, limitations and future perspectives," *Journal of Cleaner Production,* vol. 255, 2020.

[92] A.K. Jing Ji, Z. Yu, A. Khan, P. Liu, and X. Li, "Anaerobic membrane bioreactors for treatment of emerging contaminants: A review," *Journal of Environmental Management,* vol. 270, 2020.

[93] R.K. Ali Asghar Ebrahimi, H. Eslami, M. Taghavi, F. Omidi, and R.A. Fallahzadeh, "Removal of heavy metals from compost leachate using an anaerobic consecutive system of anaerobic migrating blanket reactor-anaerobic sludge bed reactor," *Desalination and Water Treatment,* vol. 271, 2022.

[94] Y.F. Xinwei Tan, X. Zhang, T. Hao, R. Chen, T. Zhang, R. Lu, J. Sun, D. Li, Y. Pan, Y. Y. Li, and Z. Kong, "Carbon-neutral potential in treatment of N, N-dimethylformamide-containing industrial wastewater: Comparative investigation of energy conservation, carbon reduction and expenditure between UASB and Fenton process," *Journal of Water Process Engineering,* vol. 56, 2023.

[95] Y.L. Yanxu Liu, H. Cheng, L. Zou, Y.Y. Li, and J. Liu, "High-efficiency anaerobic co-digestion of food waste and mature leachate using expanded granular sludge blanket reactor," *Bioresource Technology,* vol. 362, 2022.

[96] C.T. Nils Horstmeyer, T. Lippert, and J.E. Drewes, "A hydraulically optimized fluidized bed UF membrane reactor (FB-UF-MR) for direct treatment of raw municipal wastewater to enable water reclamation with integrated energy recovery," *Separation and Purification Technology,* vol. 235, 2020.

[97] Z.A. Zhao Jiang, L. Qiu, W. Li, J. Yu, Z. Xia, L. Qi, G. Liu, and H. Wang, "Enhanced wastewater treatment with an AnF-AAO system for improved internal carbon source utilization," *Chemosphere,* vol. 363, 2024.

[98] V.V.P. Tran Thi Thai Hang, N. A. Dao, H. H. Hanh, N. N. Thoai, P. T. Hung, D. V. Tri, T. L. Luu, T. H. Thuan, N. V. Tuyen, C. X. Quang, M. F. Vigile, A. Cassano, F. Galiano, and A. Figoli, "Green chemistry treatment of seafood processing wastewater using pilot scale Anaerobic Membrane Bioreactor (AnMBR) in a realtime mode," *Green Analytical Chemistry,* vol. 12, 2025.

[99] M.W. Haochun Zang, H. Li, B. Yan, and H. Peng, "Anaerobic baffled reactor (ABR) coupled step-feeding and effluent recycling for treating high concentration allicin wastewater with granulation of sludge," *Journal of Water Process Engineering,* vol. 65, 2024.

[100] J.M. S. Zhe Deng, A.L. Morgado Ferreira, D. Cerqueda-Garcia, H. Spanjers, and J.B. van Lier, "Effect of operational parameters on the performance of an anaerobic sequencing batch reactor (AnSBR) treating protein-rich wastewater," *Environmental Science and Ecotechnology,* vol. 17, 2024.

[101] I.F. Sunny Aiyuk, D.K. Lieven, A. van Haandel, and W. Verstraete, "Anaerobic and complementary treatment of domestic sewage in regions with hot climates—A review," *Bioresource Technology* vol. 97, 2006.

[102] Y.-J.X. Jun-Yuan Ji, Z. T. Ma, M. Zhang, and P. Zheng "Acute toxicity of pharmaceutical wastewaters containing antibiotics to anaerobic digestion treatment," *Chemosphere,* vol. 91, 2013.

[103] J. B. van Lier, N. A. Mahmoud, and G. Zeeman, "Anaerobic wastewater treatment," in *Biological Wastewater Treatment: Principles, Modelling and Design*, M. Henze, M. van Loosdrecht, G. A. Ekama, and D. Brdjanovic, Eds. London, U.K.: IWA Publishing, 2008, pp. 415–457.

[104] H. H. P. Fang and O.-C. Chan, "Toxicity of phenol towards anaerobic biogranules," *Water Res*., vol. 31, no. 9, pp. 2229–2242, 1997.

[105] M.Y. Jianxing Sun, H. Zhou, Z. Chen, Y. Wang and H. Cheng, "Enhanced printing and dyeing wastewater treatment using anaerobic-aerobic systems with bioaugmentation," *Journal of Hazardous Materials,* vol. 486, 2025.

[106] M.S.H.M. Shohidullah Miah, M.S. Ali, S.B. Shahid, S. Sharmin, and H.M. Zakir "Textile effluent treatment in a pilot-scale UASB bioreactor followed by biofilter and aerobic processes," *Case Studies in Chemical and Environmental Engineering,* vol. 11, 2025.

[107] Y.Z. Shuang Tong, J. Li, J. Wei, and J. Li, "Advanced removal of organics and nitrogen in upgraded anaerobic-aerobic slaughterhouse wastewater treatment process," *Desalination and Water Treatment,* vol. 308, pp. 80-89, 2023.

[108] T.K.S. Siewhui Chong, A. Kayaalp, and H.M. Ang "The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment e A State-of-the-art review," *Water Research,* vol. 46, 2012.

[109] S.W. Livia Britschgi, A. Proesl, E. Morgenroth, and N. Derlon, "The critical role of flocs in nitrification in full-scale aerobic granular sludge-based WWTP," *Water Research,* vol. 274, 2025.

[110] Waterleau. "Sustainable brewing in Colombia: How Waterleau's BIOTIM® UASB transforms Central Cervecera." *Waterleau*. [Online]. Available: https://www.waterleau.com/en/cases/sustainable-brewing-in-colombia-how-waterleaus-biotim-uasb-transforms-central-cervecera

[111] A.G. Francesco Bianco, I. Martucci, L. Pucci, and M. Race "Comparing continuous and intermittent aeration using BioWin™ model simulation in a full-scale wastewater treatment plant," *Journal of Water Process Engineering,* vol. 68, 2024.

[112] L.X. Jiansheng Huang, Y. Guo, D. Liu, S. Chen, Q. Tang, H. Zheng, J. Tan, and F. Peng "Intermittent aeration improving activated granular sludge granulation for nitrogen and phosphorus removal from domestic wastewater," *Bioresource Technology Reports,* vol. 15, 2021.

[113] J.P. Junling Pang, D. Tong, X. Fu, B. Sun, M. Yang, and H. Li, "How do hydraulic load and intermittent aeration affect pollutants removal and greenhouse gases emission in wastewater ecological soil infiltration systems?," *Ecological Engineering,* vol. 146, 2020.

[114] L.Z. Zaizhou Xu, X. Gao, and Y. Peng, "Optimization of the intermittent aeration to improve the stability and flexibility of a mainstream hybrid partial nitrification-anammox system," *Chemosphere,* vol. 261, 2020.

[115] A.B. Vijay Sodhi and M. Kumar Jha "Minimization of excess bio-sludge and pollution load in oxic-settlinganaerobic modified activated sludge treatment for tannery wastewater," *Journal of Cleaner Production,* vol. 243, 2020.

[116] K.-J. A. Guang-Hao Chen, S. Saby, E. Brois, and M. Djafer, "Possible cause of excess sludge reduction in an oxic-settling-anaerobic activated sludge process (OSA process)," *Water Research,* vol. 37, 2003.

[117] F.D.C. Raffaele Morello, G. Esposito, F. Pirozzi, U. Fratino, and D. Spasiano, "Sludge minimization in mainstream wastewater treatment: Mechanisms, strategies, technologies, and current development," *Journal of Environmental Management,* vol. 319, 2022.

[118] M.D.D.T. Hadeer Abdalla, M. Abdallah, M. Sartaj, and R. Hamza, "Optimizing aerobic granular sludge process performance: Unveiling the power of coupling experimental factorial design methodology with artificial intelligence modeling," *Journal of Water Process Engineering,* vol. 61, 2024.

[119] G.Z. Shanyun Wang, Y. Li, X. Wang, J. Zhou, and Y. Peng, "Robustness of anammox granular sludge treating low-strength sewage under various shock loadings: Microbial mechanism and little N2O emission," *Journal of Environmental Sciences,* vol. 86, 2019.

[120] L.B. Elisa Clagnan, S. Pioli, S. Visigalli, A. Turolla, M. Jia, M. Bargna, E. Ficara, G. Bergna, R. Canziani, and M. Bellucci "Microbial community and performance of a partial nitritation/anammox sequencing batch reactor treating textile wastewater," *Heliyon,* vol. 7, 2021.

[121] L.Z. Cancan Jiang, Y. Chi, S. Xu, Y. Xie, D. Yang, Y. Qian, F. Chen, W. Zhang, D. Wang, Z. Tian, S. Zhang, Y.Y. Li, and X. Zhuang, "Rapid start-up of an innovative pilot-scale staged PN/A continuous process for enhanced nitrogen removal from mature landfill leachate via robust NOB elimination and efficient biomass retention," *Water Research,* vol. 249, 2024.

[122] R.M. Huihua Lin, Y. Hu, J. Lin, S. Sun, J. Jiang, T. Li, and J. L. Qinxiong Liao, "Reviewing bottlenecks in aerobic granular sludge technology: Slow granulation and low granular stability," *Environmental Pollution,* 2020.