Al-Furat Journal of Innovations in Agricultural Sciences (FJIAS)
https://doi.org/10.46649/fjias.v2i1.005

Aerobic and Anaerobic Biological Processes for Wastewater Treatment: Technologies, Performance Evaluation and Future Perspectives

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Received (05/01/2026), Received in revised form (01/03/2026)
Accepted (14/03/2026), Available online (19/03/2026)

FJIAS 2026, 2(1): 44-62

Abstract. *Wastewater has proven to be one of the key environmental issues facing the world today as a result of the increasing amounts of untreated domestic, agricultural, and industrial wastewaters being discharged into the environment. Inefficient management of wastewater has been identified as posing serious risks to environmental sustainability. Among the various wastewater treatment processes, the biological processes have been widely used as they are cost-effective, easy to operate, environmentally friendly, and involve less energy and chemical usage.*

This study is aimed at providing a comprehensive review of aerobic and anaerobic biological processes used in the treatment of wastewater with special emphasis on advanced aerobic and anaerobic reactor processes, including the Upflow Anaerobic Sludge Blanket (UASB), Expanded Granular Sludge Bed (EGSB), and the combination of anaerobic and aerobic processes. This study will examine the operational mechanisms, efficiencies, advantages, and limitations of the processes based on the existing scientific literature.

Additionally, the study will examine the shortcomings of the existing biological processes and how the combination of aerobic and anaerobic processes can improve the efficiency of the processes while minimizing sludge production and increasing the resource recovery potential through the production of biogas. This study has established that the combination of anaerobic and aerobic processes can be used as a sustainable approach to the management of wastewater, especially in the developing world.

Keywords: *Wastewater Treatment; Biological Degradation; Aerobic Treatment; Anaerobic Digestion; UASB Reactor; EGSB Reactor; Hybrid Treatment Systems .*

1. INTRODUCTION

Wastewater management is one of the critical challenges in the development of many of the world’s developing nations in terms of environmental sustainability and public health concerns. Consequently, the ineffective management of wastewater has been identified as a significant threat to the sustainability of the environment and public health.

Domestic and urban wastewater are typically characterized as containing considerable amounts of biodegradable organic pollutants, which include Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD5), and Chemical Oxygen Demand (COD), among others, and are usually considered critical in determining the extent of pollution in the wastewater.

In arid regions where water is a scarce resource, wastewater reuse has been identified as a critical factor in the management of water resources in those regions for sustainability purposes. Thus, it is critical to treat the wastewater before it is discharged or reused for sustainability purposes[1-3].

Wastewater treatment technologies can be generally classified into three main categories, which include physical, chemical, and biological treatment methods. Although the application of physical and chemical treatment methods is common worldwide, many studies have indicated that biological treatment methods can be the best option in terms of efficiency, cost-effectiveness, and environmental sustainability[4-6].

The biological treatment methods involve the application of metabolic activities of microorganisms to convert the organic matter into simpler and stable forms. The biological treatment methods can be carried out under aerobic, anaerobic, and facultative conditions, depending on the wastewater type and treatment efficiency [7-9]. In recent years, there has been significant interest in the application of high-rate biological treatment reactors such as the Upflow Anaerobic Sludge Blanket (UASB) and Expanded Granular Sludge Bed (EGSB) reactors due to the capability to treat huge amounts of organic waste and produce energy in the form of biogas [10-12].

Although the application of biological treatment technologies is common worldwide, the choice of the best method depends on the wastewater type, treatment efficiency, operating costs, and environmental regulations. In this context, the main parameters used to evaluate the wastewater type and treatment efficiency include physical, chemical, and microbiological parameters, as presented in Table 1 [13-15].

Table 1. Classification of Wastewater Treatment Processes

Treatment Category	**Key Monitoring Parameters**
Physical treatment	TS, TSS, Turbidity, pH
Chemical treatment	COD, BOD, TN, TP
Microbiological	Total coliforms, fecal coliforms

2. METHODOLOGY OF LITERATURE REVIEW

This review has been conducted through the analysis of various publications on biological wastewater treatment technologies. Scientific databases including Scopus, Web of Science, and Google Scholar were used to collect relevant studies published between 2022 and 2026. Keywords such as aerobic treatment, anaerobic digestion, UASB reactor, EGSB reactor, and wastewater biological treatment were used during the search process. More than

120 research articles and technical reports were screened, and the most relevant studies were selected for detailed analysis.

3. BIOLOGICAL WASTEWATER TREATMENT TECHNOLOGIES

Biological wastewater treatment technologies are considered to be one of the most frequently applied methods of removal of organic pollutants from wastewater. The biological wastewater treatment processes are based on the metabolic activities of microorganisms, which convert biodegradable organic pollutants into simpler and more stable end-products, including carbon dioxide, methane, water, and biomass. The biological wastewater treatment processes are considered to be more economical, eco-friendly, and able to provide high removal efficiency of pollutants using low amounts of chemicals compared to physical and chemical treatment processes [16].

Microorganisms in biological treatment systems use the organic stuff in wastewater as food to thrive and reproduce. There are two kinds of biological reactions: aerobic, which means adding oxygen to the reaction, and anaerobic, which means not adding oxygen to the reaction. The choice of the best biological technology for the treatment of wastewater depends on various factors such as the composition of the wastewater, organic loading rate, and environmental factors [17].

A wide variety of biological reactor configurations has been developed to enhance the efficiency of the process and the reliability of the operation of the biological process. Some of the widely used aerobic biological technologies include activated sludge (AS) systems, rotating biological contactors (RBC), membrane bioreactors (MBR), sequencing batch reactors (SBR), and moving bed biofilm reactors (MBBR), which are effective in the removal of organic matter and nutrients from wastewater with low organic loading rates [18].

On the other hand, anaerobic biological treatment systems have increasingly been recognized over the past decades owing to their ability to treat wastewater with high concentrations of organics while producing renewable energy through biogas production. For instance, high-rate anaerobic reactors such as the Upflow Anaerobic Sludge Blanket reactor and Expanded Granular Sludge Bed reactor have been recognized to have substantial potential to treat municipal and industrial wastewater, especially in regions with warm climates [9,13].

Figure 1 below illustrates the major classification of biological wastewater treatment systems and their relationship with aerobic, anaerobic, and hybrid treatment technologies. It is evident that there are aerobic treatment systems, anaerobic treatment systems, and hybrid anaerobic-aerobic treatment systems, each with its own operational benefits depending on wastewater quality and treatment objectives.

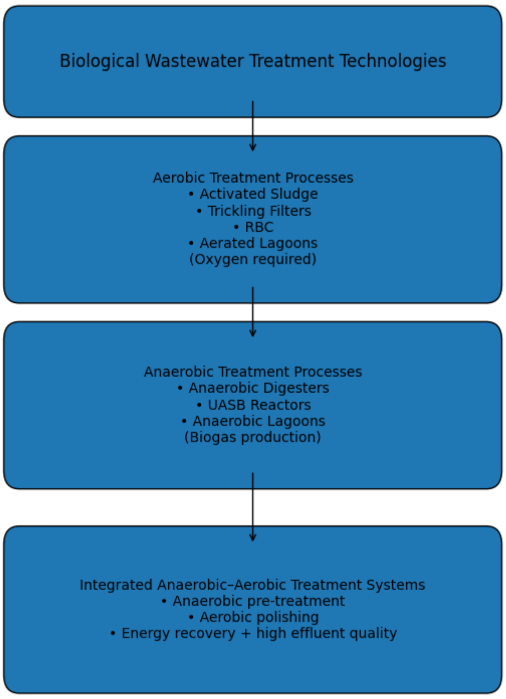

Figure 2. Classification of biological wastewater treatment technologies including aerobic, anaerobic, and integrated treatment systems

Generally, the performance of biological treatment technologies can be determined using different wastewater quality parameters such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), Such parameters are often used to determine the effectiveness of wastewater treatment technologies and system stability. A general classification of wastewater treatment methods and parameters is shown in Table 1 below.

Despite the benefits associated with conventional biological treatment systems, there are various operational problems associated with biological treatment technologies, such as long hydraulic retention times, large land use requirements, and low energy production potential from aerobic treatment systems. Therefore, various researchers have focused on developing high-rate biological reactors and hybrid treatment technologies to improve removal efficiency while reducing operational costs [3,13].

4. CHARACTERISTICS OF DOMESTIC WASTEWATER

Wastewater generated in domestic settings mainly results from activities such as bathing, cooking, laundry, and sanitation, with the possibility of some contribution from small-scale commercial activities and stormwater infiltration. The composition of domestic wastewater varies depending on factors such as water consumption rates, population density, and lifestyle, as well as the extent of industrial activities in the vicinity and the state of the sewer network. In general, domestic wastewater consists of approximately 99.9% water and 0.1% solids, which include both organic and inorganic substances. These compounds include biodegradable organic matter, nutrients such as nitrogen and phosphorus, suspended matters, microorganisms, and trace levels of metals such as those of the heavy category, which originate from both domestic and industrial sources [1,4].

The levels of organic compounds in domestic wastewater are usually determined and expressed as Biochemical Oxygen Demand (BOD5) and Chemical Oxygen Demand (COD), which indicate the oxygen demand required for the biological and chemical oxidation of organic compounds in water. Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), and pathogenic organisms are also widely used to determine the quality of wastewater. Table 2 presents the typical physicochemical composition of domestic wastewater, which includes the ranges of concentrations of the most commonly determined compounds in the context of wastewater treatment processes.

Table 2. Typical Physicochemical Characteristics of Domestic Wastewater

Parameter	Typical Concentration Range (mg/L)
Total Suspended Solids (TSS)	250 – 400
Total Dissolved Solids (TDS)	250 – 850
Total Solids (TS)	350 – 1200
Biochemical Oxygen Demand (BOD_5)	100 – 300
Chemical Oxygen Demand (COD)	250 – 800
Total Nitrogen (TN)	20 – 85
Total Phosphorus (TP)	6 – 25
Oils and Grease	100 – 200
Chlorides	30 – 100
Alkalinity	50 – 200
Fecal Coliforms	$2 \times 10^6 – 3 \times 10^7$ /100 mL
Chromium (Cr)	0.1 – 0.5
Copper (Cu)	0.2 – 0.5
Lead (Pb)	0.08 – 0.4
Zinc (Zn)	0.4 – 0.7

5. COMPARATIVE ANALYSIS OF AEROBIC AND ANAEROBIC WASTEWATER TREATMENT PROCESSES

Wastewater treatment processes using biological treatment can be broadly classified into aerobic and anaerobic treatment processes, depending on the presence or absence of dissolved oxygen for microbial activity. These two treatment processes are different from each other with regard to operational characteristics, treatment efficiency, and energy consumption. These differences make these two treatment processes applicable for different wastewater treatment needs [19-21].

Several studies have demonstrated that aerobic treatment systems achieve high removal efficiencies for BOD and COD, while anaerobic systems offer lower sludge production and energy consumption [22–24].

5.1. AEROBIC TREATMENT PROCESSES

Wastewater treatment using an aerobic treatment system involves microorganisms that need oxygen to carry out the degradation of organic pollutants in wastewater. In this treatment system, oxygen is provided to microorganisms using artificial aeration. This helps in the degradation of organic pollutants into carbon dioxide, water, and biomass [1].

Activated Sludge Process (ASP), Sequencing Batch Reactor (SBR), Rotating Biological Contactor (RBC), Moving Bed Biofilm Reactor (MBBR), and Membrane Bioreactor (MBR) are some of the major aerobic treatment processes used in wastewater treatment. These treatment technologies are commonly used for wastewater treatment because of their high efficiency for the removal of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) from wastewater [3].

Aerobic treatment processes are highly effective for producing high-quality effluent and for the removal of dissolved organic matter. In addition, these treatment processes are highly effective for nutrient removal, which is critical for meeting stringent environmental discharge requirements. However, these treatment processes are highly energy-intensive and also produce high amounts of sludge for treatment and disposal [3,13].

5.2 *Anaerobic Treatment Processes*

The wastewater treatment process in an anaerobic treatment plant is carried out in the absence of oxygen and is due to the presence of a complex microbial population, which is responsible for degrading wastewater. The biochemical process of anaerobic digestion involves different steps, i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis, which convert wastewater into methane and carbon dioxide [11].

The use of high-rate anaerobic treatment plants like Upflow Anaerobic Sludge Blanket (UASB) and Expanded Granular Sludge Bed (EGSB) reactors is well documented for treating wastewater with high rates of organic loading. These treatment plants offer numerous benefits over conventional aerobic treatment plants: low operational energy requirement, less sludge production, and production of renewable energy in the form of biogas [9, 13].

The treatment of wastewater with high levels of organic pollutants (COD > 2000-4000 mg/L) is more efficiently done in anaerobic treatment plants. Nevertheless, compared to aerobic treatment plants, the treated water is of poor quality and may demand additional treatment in aerobic treatment plants to meet discharge requirements [15].

5.3 *Operational Comparison Between Aerobic and Anaerobic Systems*

The operational performance of aerobic and anaerobic treatment plants is significantly different in terms of operational energy requirement, sludge production, treatment efficiency, and operational complexity. Aerobic treatment plants demand more operational energy in terms of aeration of wastewater compared to anaerobic treatment plants. On the other hand, aerobic treatment plants achieve better treatment efficiency compared to anaerobic treatment plants. Anaerobic treatment plants demand less operational energy and produce less sludge while simultaneously generating methane-rich biogas that can be used as renewable energy [3, 9].

The differences between aerobic and anaerobic treatment systems in terms of sludge generation and biogas production are illustrated in Figure 2

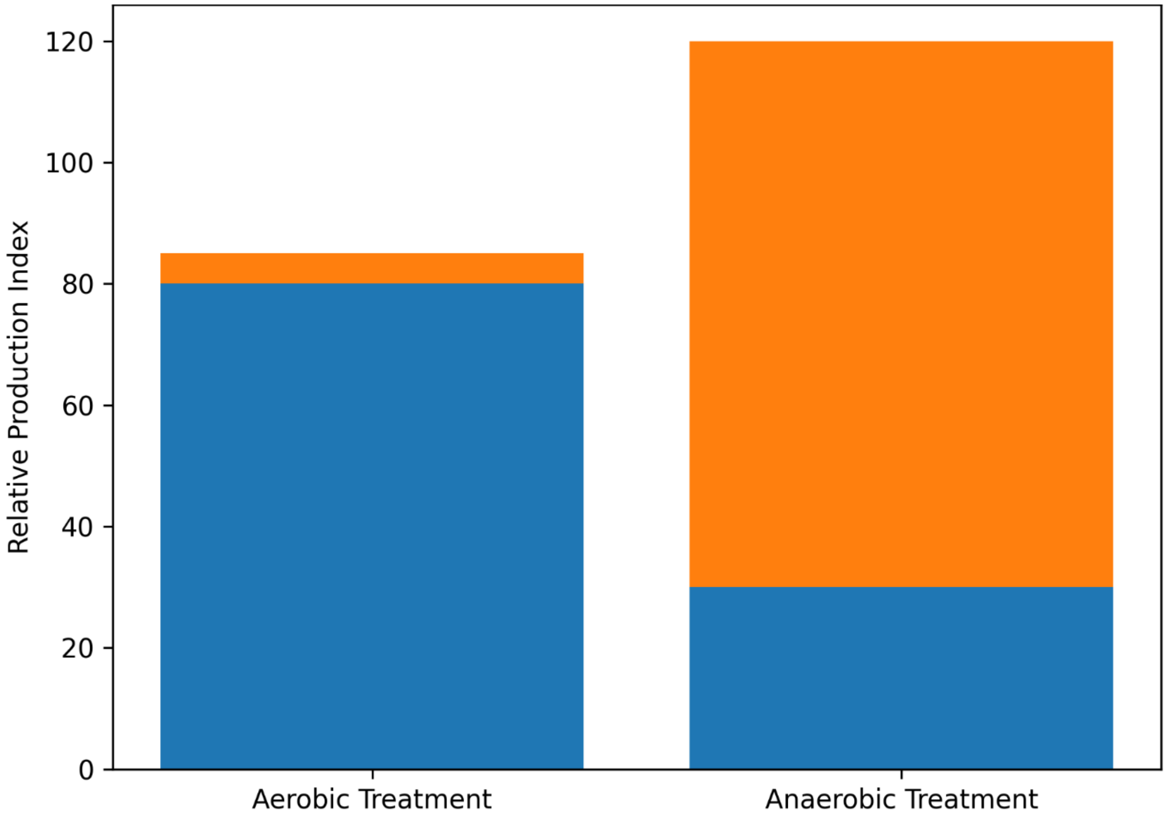

Figure 2. Comparison between aerobic and anaerobic wastewater treatment processes in terms of sludge generation and biogas production

In terms of sludge generation, aerobic treatment facilities tend to produce more biological sludge because of the higher growth rate of microorganisms, whereas anaerobic treatment facilities tend to produce less biological sludge because of the lower growth rate of microorganisms.

5.4 *Advantages and Limitations of Each Process*

Aerobic and anaerobic wastewater treatment technologies have individual advantages and disadvantages depending on wastewater characteristics and operational conditions. For example, aerobic treatment is recommended for low-strength wastewater treatment where high-quality effluent is required. On the contrary, anaerobic treatment is recommended for high-strength industrial wastewater treatment and for situations where energy production is desirable.

Although aerobic and anaerobic treatment technologies have individual advantages, it is not possible for either of the treatment technologies to offer maximum performance under all conditions. Therefore, modern wastewater treatment technologies and practices focus more on combined anaerobic and aerobic treatment technologies for better performance and maximum benefits of wastewater treatment and resource production.

A comparative summary of key performance characteristics of aerobic and anaerobic wastewater treatment technologies is presented in Table 3.

Table 3. Comparative Performance of Aerobic and Anaerobic Wastewater Treatment Processes**.**

Parameter	**Aerobic Treatment Processes**	**Anaerobic Treatment Processes**
Oxygen requirement	Requires continuous oxygen supply through aeration	Operates in the absence of oxygen
Typical organic loading rate	Low to moderate	High organic loading rates
COD removal efficiency	High (85–95%)	Moderate to high (65–90%)
BOD removal efficiency	Very high (90–98%)	Moderate (70–90%)
Sludge production	High sludge generation due to rapid microbial growth	Low sludge production
Energy consumption	High due to aeration requirements	Low energy requirement
Biogas production	No biogas generation	Produces methane-rich biogas
Start-up period	Short start-up time	Longer start-up period due to slow microbial growth
Effluent quality	High-quality effluent suitable for discharge	Effluent may require post-treatment
Nutrient removal	Effective removal of nitrogen and phosphorus	Limited nutrient removal
Operational complexity	Moderate to high	Relatively simple operation
Sensitivity to temperature	Less sensitive	Highly sensitive to temperature changes
Application suitability	Municipal wastewater and low-strength wastewater	High-strength industrial wastewater

6. HIGH-RATE ANAEROBIC REACTORS

High-rate anaerobic reactors have been found to be of great interest in the treatment of wastewater, considering their ability to handle high organic loading rates while maintaining short hydraulic retention times. High-rate anaerobic reactors are based on the retention of a highly active biomass, thus allowing for the efficient degradation of organic pollutants under anaerobic conditions. High-rate anaerobic reactors have been found to be better than conventional anaerobic digesters, considering their enhanced treatment efficiency, reduced reactor volume, and increased methane production, thus making them suitable for treating both municipal and industrial wastewater of high organic strength [25-27].

Among the many high-rate anaerobic reactors developed over the past few decades, the Upflow Anaerobic Sludge Blanket (UASB) reactor and the Expanded Granular Sludge Bed (EGSB) reactor are found to be the most commonly used anaerobic treatment systems. High-rate anaerobic reactors, such as the UASB reactor and EGSB reactor, use granular sludge, thus allowing for the separation of the anaerobic biomass from the treated effluent, thus ensuring reactor stability under high organic loading rates. This reactor design has been found to enhance the efficient contact between the wastewater and the anaerobic biomass, thus ensuring enhanced treatment efficiency.

6.1. UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR

The Upflow Anaerobic Sludge Blanket reactor is one of the commonly used anaerobic reactors for treating wastewater. It is based on an anaerobic treatment system that originated in the late 1970s and early 1980s. This reactor system cleans up wastewater by moving it up through a thick layer of anaerobic sludge granules that are home to a wide range of anaerobic bacteria that are very important for breaking down pollutants. [28-30].

During treatment, microorganisms react with contaminants to produce simpler compounds through a series of sequential biochemical reactions: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. At the end of the reactions, contaminants are converted to methane gas and carbon dioxide gas, which can be utilized as a renewable energy source [11].

A crucial component of the UASB reactor is the gas-liquid-solid (GLS) separator. It is essential to note that this component is crucial to the separation of biogas, treated wastewater, and sludge particles. It allows biogas to escape from the reactor while retaining sludge particles inside the reactor. This design ensures that there is a concentrated biomass concentration for the efficient treatment of contaminants. A schematic diagram of the reactor design is shown in Figure 3.

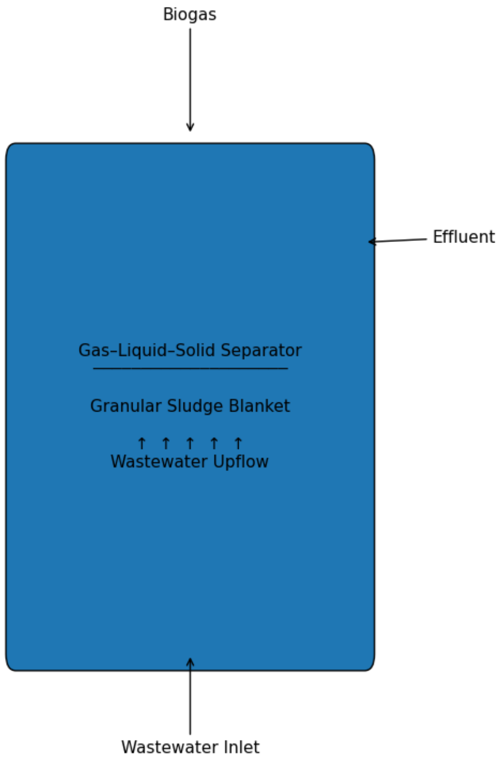

Figure 3. Schematic diagram of the Upflow Anaerobic Sludge Blanket (UASB) reactor used for biological wastewater treatment

The Upflow Anaerobic Sludge Blanket (UASB) reactor is effective in treating wastewater containing moderate to high-strength contaminants. In addition, the reactor is commonly used in treating wastewater with temperatures between 20-30°C. This temperature is typical for wastewater in warm climates. Under optimal conditions of temperature, it is evident that 65-85% of COD is removed from wastewater using UASB reactors; however, it is dependent on wastewater strength [13; 20].

Although UASB reactors are effective in treating wastewater with moderate and high-strength contaminants, there are various operational problems that are experienced in UASB reactor treatment processes. For instance, UASB reactors are sensitive to temperature fluctuations and are also prone to sludge loss. Moreover, UASB reactors are not effective in treating wastewater with low-strength contaminants. Therefore, UASB reactors may be used in combination with aerobic reactors to improve effluent quality to meet environmental discharge standards [15].

6.2 Expanded Granular Sludge Bed (EGSB) Reactor

The Expanded Granular Sludge Bed (EGSB) reactor is considered an upgraded version of the UASB reactor, aiming to mitigate some of the operational problems associated with the UASB process. The EGSB process operates with higher upflow velocities, which enhance the mixing process and the interaction between the wastewater and the granular sludge. This results in higher levels of efficiency, mainly for wastewaters with lower concentrations of organics [31-33].

Wastewater enters the EGSB reactor from the bottom and flows upward with high velocity, ranging between 6 and 15 m h^{-1}. This high velocity increases the bed volume of the granular sludge, thereby improving the mass transfer between the microorganisms and the organic substrate. This improved mixing environment enables the EGSB reactor to maintain high biomass activity and eliminates the development of dead zones, which are usually encountered in conventional UASB reactors [13].

The EGSB reactor has the advantage of having the gas, liquid, and solid phases separated, similar to the conventional UASB process. However, the high height of the EGSB reactor and the high velocity of the wastewater enable the sludge to be suspended, thereby improving the hydrodynamics of the process.

Different investigations on the EGSB technique have shown that it works well to get rid of COD, with rates greater than 70–85%. These studies suggest that the EGSB procedure is a good way to clean wastewater from cities. Also, the EGSB process has been demonstrated to work better with low temperatures and diluted wastewaters than standard UASB processes [31].

However, the EGSB process has the disadvantage of having high capital costs and requires careful control to avoid excessive sludge washout, which results from the high velocity of the process. Nevertheless, the improved performance of the EGSB process makes the technology promising for the development of modern anaerobic wastewater treatment processes.

The hydrodynamic structure and operational principle of the EGSB reactor are illustrated in Figure 4.

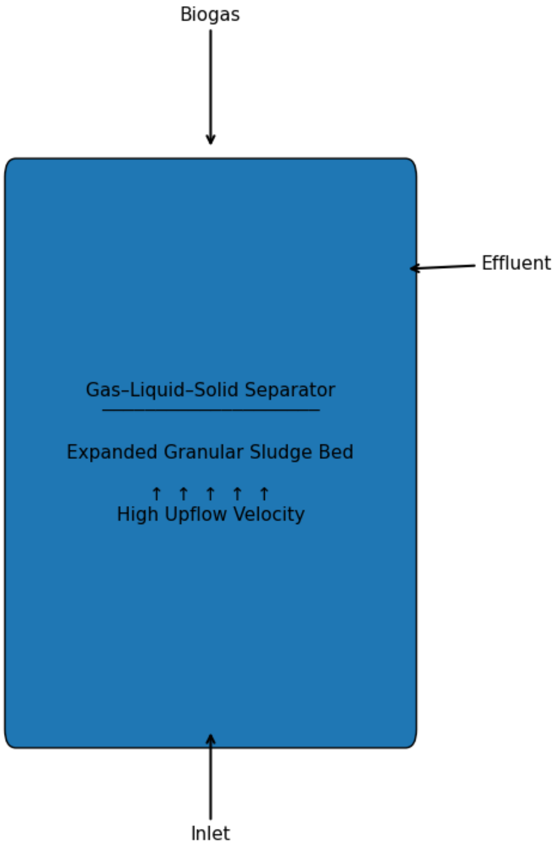

Figure 4. Schematic configuration of the Expanded Granular Sludge Bed (EGSB) reactor showing the expanded sludge bed and upward flow of wastewater

7. INTEGRATED ANAEROBIC–AEROBIC TREATMENT SYSTEMS

Integrated anaerobic and aerobic treatment systems have been proposed and implemented for effective wastewater treatment by taking advantage of the merits of both anaerobic and aerobic treatment technologies. In integrated treatment systems, wastewater is subjected to anaerobic treatment, followed by aerobic treatment. In the anaerobic treatment process, a significant percentage of organic matter is degraded and converted into gases. The treated wastewater is then subjected to the aerobic treatment process for polishing treatment, thereby reducing organic matter, suspended solids, and nutrients [34-36].

Both anaerobic and aerobic processes have advantages in the treatment of wastewater. Anaerobic process has the advantage of reducing the organic content and generating energy in the form of methane gas. During the aerobic process, the removal rates of Biochemical Oxygen Demand (BOD5), Chemical Oxygen Demand (COD), and nutrients such as nitrogen and phosphorus are improved. In integrated treatment systems, the removal efficiency of organic matter is higher, and sludge and energy consumption are less compared to conventional treatment systems [13].

A number of configurations of integrated treatment systems have been extensively studied and implemented in wastewater treatment plants. These configurations of integrated treatment systems include UASB-Activated Sludge (UASB-AS), UASB-Sequencing Batch Reactor (UASB-SBR), and UASB-Aerated Biofilter (UASB-ABF) systems. In all of these configurations of hybrid treatment systems, the anaerobic reactor is used as a major treatment component to remove a large fraction of organics from wastewater, while the aerobic reactor is used as a polishing component to comply with environmental discharge regulations [15].

The performance of integrated anaerobic-aerobic treatment systems is affected by various operational parameters such as hydraulic retention time, organic loading rate, temperature, and reactor design. With the right design for anaerobic-aerobic treatment systems, it is possible to remove more than 90% of COD while keeping running costs low and generating energy through biogas production [20].

With optimum removal efficiencies and energy production potentials of integrated anaerobic-aerobic treatment systems, it is increasingly considered a viable solution to sustainable wastewater treatment practices, especially in developing regions where energy consumption and operating costs are major concerns. A schematic presentation of a typical integrated anaerobic-aerobic wastewater treatment system is given in Figure 5.

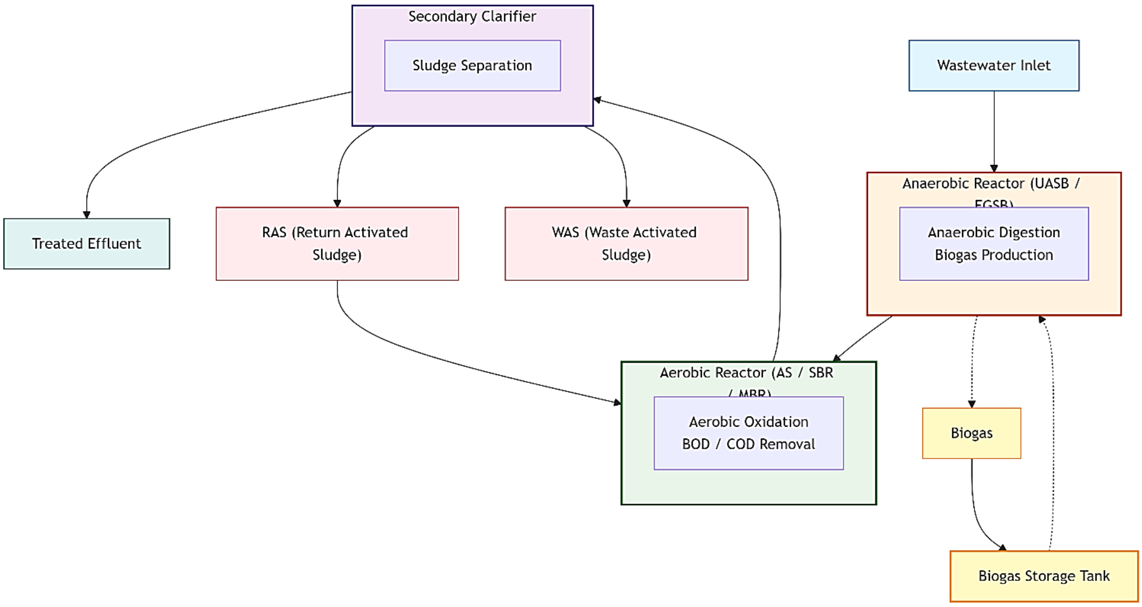

Figure 5. Schematic diagram of an integrated anaerobic–aerobic wastewater treatment system showing sequential treatment through anaerobic digestion followed by aerobic polishing and final clarification.

8. DISCUSSION

A comparison is made on aerobic and anaerobic wastewater treatment methods and their respective advantages and disadvantages. Aerobic treatment is often used in wastewater treatment plants and is effective in treating biodegradable materials and nutrients from wastewater with high BOD5, COD removal, and oxidation of ammonia through nitrification. However, it requires more oxygen to be used during treatment, thus increasing costs [3].

On the contrary, anaerobic wastewater treatment technologies are highly beneficial for the removal of organic pollutants from wastewater, particularly in situations where high organic loading rates are present in wastewater. The use of anaerobic wastewater treatment technologies, such as Upflow Anaerobic Sludge Blanket (UASB) and Expanded Granular Sludge Bed (EGSB) processes, is highly beneficial in removing organic pollutants from wastewater, producing a high amount of methane gas, which is a renewable source of clean energy. Moreover, anaerobic wastewater treatment technologies produce less sludge and require less aeration energy compared to aerobic processes. The use of anaerobic wastewater treatment technologies has been highly recommended in recent decades due to their efficiency in producing clean energy in addition to removing organic pollutants from wastewater [37-39].

However, anaerobic wastewater treatment processes are not efficient in producing high-quality effluent that can meet environmental discharge standards, particularly in terms of organic matter, suspended solids, and nutrients. This is a major drawback of anaerobic wastewater treatment processes, which requires additional treatment processes to improve the quality of effluent. Hence, a combination of both anaerobic and aerobic wastewater treatment processes is highly recommended to eliminate the disadvantages of both processes.

Consequently, combined anaerobic-aerobic wastewater treatment systems provide a comprehensive and effective method for wastewater treatment. In this system, the anaerobic treatment stage is considered to be the major treatment step, which significantly reduces the organic content of wastewater. The aerobic treatment stage is considered to be the polishing step, which removes all the remaining organic matter from wastewater.

Moreover, the implementation of high-rate anaerobic treatment systems, such as UASB and EGSB, during the initial treatment step can significantly retain biomass and maintain stable system performance under high organic loading rates. The implementation of this system can remove more than 90% COD from wastewater, making it suitable for wastewater treatment.

Thus, integrated anaerobic-aerobic treatment systems are considered to be more sustainable compared to traditional treatment systems. The execution of this technique can markedly diminish greenhouse gas emissions and carbon footprint. The generation of biogas through anaerobic treatment can serve as an alternative energy source. Moreover, this system can significantly reduce sludge handling and disposal costs. The generation of less sludge during anaerobic treatment is considered to be one of the major advantages of this system [40].

Overall, it is concluded that the results of the investigations discussed in this paper review demonstrate that hybrid anaerobic-aerobic treatment systems hold promise in solving current wastewater treatment problems. Future investigations should focus on optimizing reactor design, improving biomass retention systems, and developing sophisticated monitoring and control techniques.

9. RESEARCH GAPS AND FUTURE PERSPECTIVES

Nevertheless, there are still some areas for future research to bridge the gaps and move towards the direction of maximum efficiency and sustainability in wastewater treatment.

The first area for future research is the sensitivity of anaerobic microbes to temperature, pH, and organic loading rates. For example, UASB and EGSB systems are efficient under constant and favorable temperature, but their efficiency is low under cold climate conditions and variable wastewater composition. Therefore, there is still much to be done to improve the adaptability of anaerobic microbes.

The second area for future research is the treatment of low-strength wastewater using anaerobic systems. Anaerobic systems are very efficient in treating high-strength wastewater, but their efficiency is low in treating low-strength wastewater. Therefore, there is still much to be done to improve the efficiency of anaerobic systems under low-strength conditions.

The third area for future research is the combination of anaerobic and aerobic treatment systems. This combination is very efficient, but its design and operational parameters need to be optimized to improve its efficiency and effectiveness. Some of the design and operational parameters are hydraulic retention time, organic loading rate, sludge recycling rate, and reactor configuration.

The other important area for future research is to maximize the benefits of biogas and methane production to improve the sustainability of energy production. Therefore, there is still much to be done to maximize biogas and methane production and to find better and innovative ways of utilizing them.

Finally, there is still much to be done to improve the efficiency and effectiveness of wastewater treatment using intelligent monitoring and control systems, such as artificial intelligence, machine learning, and Internet of Things.

The other important area for future research is to conduct techno-economic evaluations of combined treatment systems under practical conditions.

10. CONCLUSION

Biological wastewater treatment is an effective method of reducing organic pollution and water resource conservation. In this paper, a comparative review of biological wastewater treatment methods has been discussed with specific reference to aerobic and anaerobic treatment systems, including high-rate anaerobic treatment systems.

Aerobic treatment systems dominate over anaerobic treatment systems owing to the higher removal efficiency of biodegradable organics and the production of good quality effluent. However, it has a drawback of requiring higher energy inputs to supply oxygen to the system and producing more sludge. On the other hand, anaerobic treatment systems such as UASB and EGSB require less energy input to the system, produce less sludge, and produce good quality methane gas that is utilized to produce renewable energy.

No single treatment system is considered best under all circumstances. Integrated treatment technologies that use anaerobic and aerobic treatment systems have an advantage over other technologies. In this system, anaerobic treatment reduces sludge production and generates methane gas that is utilized to produce renewable energy. Aerobic treatment is advantageous as it polishes the effluent to produce good quality water to be used in water treatment plants.

Using high-rate anaerobic treatment as a pre-treatment system and aerobic treatment as a secondary treatment system is advantageous as it increases removal efficiency with less energy consumption. Hence, it is considered an efficient solution to solve problems of wastewater treatment plants of today.

DECLARATION OF COMPETING INTEREST

None

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