Chapter

Biological Treatment Techniques for Sewage: Aerobic and Anaerobic Processes

Ernest Mbamalu Ezeh, Peter Chinedu Agu and Epere Aworabhi

Abstract

Sewage treatment is crucial to safeguard public health and the environment. Various techniques are available for treating wastewater, and the selection of one often depends on factors like the wastewater composition, environmental conditions, and treatment objectives. One of the most widely used methods of biological treatment for sewage is activated sludge, which employs aerobic bacteria to degrade organic matter. This process involves blending wastewater with a mixture of bacteria and flocs, with the bacteria consuming the organic matter to produce clear water while the flocs settle. Another commonly employed method is anaerobic digestion, which employs anaerobic bacteria to decompose organic matter in the absence of oxygen. These methods generate biogas, containing methane and carbon dioxide, and digestate, a nutrient-rich sludge suitable as soil amendment or fertilizer. This chapter explores the mechanisms and applications of activated sludge and anaerobic digestion in biological sewage treatment, highlighting their advantages and downsides, the factors that influence their performance, such as pH, temperature, and substrate concentration. It covers the latest improvements in biological sewage treatment, including the use of new microbial strains and hybrid treatment systems.

Keywords: sewage management, biological sewage treatment, microorganisms, biogas, digestate

1. Introduction

The treatment of sewage is a crucial aspect of modern public health and environmental protection. Effective sewage management is essential to prevent the spread of diseases and to protect water resources, which are vital for human consumption, agriculture, and industrial use. The evolution of sewage management has been driven by the need to mitigate the adverse effects of untreated wastewater on ecosystems and human communities [1, 2]. Untreated sewage contains a variety of contaminants, including pathogens, organic matter, nutrients, and toxic substances, which can lead to severe environmental degradation and health issues if released into natural water bodies [3].

Historical developments highlight the transition from rudimentary disposal methods to sophisticated treatment processes, underscoring the growing understanding of sewage's impact on water bodies and public health [4]. In ancient times, sewage was often disposed of in nearby water bodies without any treatment, leading to severe pollution and health problems [5, 6]. The Industrial Revolution marked a significant turning point, as the increased urbanization and industrial activities resulted in larger volumes of wastewater, necessitating more systematic treatment approaches [6]. Early methods focused primarily on physical processes such as sedimentation and filtration [2]. However, it became evident that these methods were insufficient to remove dissolved organic matter and pathogens [5]. The development of biological treatment processes in the late nineteenth and early twentieth centuries represented a major advancement, as these processes could effectively reduce organic pollutants through the activity of microorganisms [6].

Biological treatment processes, which harness the natural activities of microorganisms to degrade organic pollutants, have become fundamental in modern sewage treatment systems. These processes are categorized broadly into aerobic and anaerobic treatments, each with distinct mechanisms and applications [7]. The literature indicates that aerobic treatment, particularly the activated sludge process, has been extensively adopted due to its effectiveness in reducing organic matter and its adaptability to varying wastewater compositions [8, 9]. The activated sludge process operates on the principle of maintaining a suspended growth system where aerobic bacteria consume organic pollutants, forming flocs that can be easily separated from the treated water [10]. The activated sludge process involves several stages, including aeration, sedimentation, and sludge recycling [11]. During the aeration stage, wastewater is mixed with a microbial culture in the presence of oxygen. Aerobic bacteria metabolize the organic matter, converting it into carbon dioxide, water, and biomass. The resulting microbial flocs are then separated from the treated water in the sedimentation stage [6]. Some of the settled sludge is recycled back to the aeration tank to maintain a high concentration of microorganisms, while the excess sludge is removed for further treatment or disposal. This process not only reduces organic pollutants but also helps in the removal of nitrogen and phosphorus, which are important for preventing eutrophication in receiving waters [9].

Anaerobic digestion, another widely researched and applied biological treatment method, leverages anaerobic bacteria to decompose organic matter in the absence of oxygen [12]. This process not only reduces the volume of waste but also produces biogas, a valuable by-product that can be utilized for energy generation [6]. The anaerobic digestion process occurs in several stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex organic molecules are broken down into simpler compounds [13]. Acidogenesis and acetogenesis further convert these compounds into volatile fatty acids, hydrogen, and carbon dioxide. Finally, during methanogenesis, methanogenic bacteria produce methane and carbon dioxide from these intermediates. The digestate resulting from anaerobic digestion is nutrient-rich and can be used as fertilizer or soil amendment, adding an economic benefit to the environmental advantages. Anaerobic digestion is particularly suited for treating high-strength wastewater and sludge due to its ability to handle high organic loads and produce valuable by-products. Additionally, it generates less excess sludge compared to aerobic processes, reducing the need for sludge handling and disposal [14].

The performance of these biological treatment processes is influenced by various factors, including temperature, pH, and substrate concentration. Research has shown that optimizing these parameters can significantly enhance treatment efficiency and stability [15, 16]. For instance, temperature affects the metabolic rates of microorganisms, with mesophilic and thermophilic conditions being optimal for different types of bacteria. pH levels can influence microbial activity and the solubility of nutrients and toxins. Substrate concentration, or the amount of organic matter available for microbial consumption, must be balanced to prevent overloading the system and to ensure efficient degradation [17]. Recent advancements in the field have focused on the development of new microbial strains with enhanced degradation capabilities and the integration of hybrid systems that combine aerobic and anaerobic processes to capitalize on the strengths of both methods [15]. For example, genetically engineered microorganisms and microbial consortia have been developed to degrade specific pollutants more efficiently. Hybrid systems, such as sequential batch reactors and membrane bioreactors, integrate aerobic and anaerobic stages to achieve higher treatment efficiencies and resource recovery [17]. Therefore, this chapter aims to provide a comprehensive overview of the mechanisms, applications, and performance factors of activated sludge and anaerobic digestion processes. These innovations aim to address the limitations of conventional treatment methods and improve the sustainability of sewage treatment practices.

2. Basics of biological sewage treatment

2.1 Definition and principles

Biological sewage treatment refers to the use of microorganisms to remove contaminants, primarily organic matter from wastewater [18]. This process relies on the metabolic activities of various microorganisms to degrade and convert pollutants into stable forms [19]. The principles underlying biological sewage treatment include:

a. Biochemical oxygen demand (BOD) reduction: Microorganisms consume organic matter in the wastewater, thereby reducing the BOD, which is a measure of the amount of oxygen required to biologically decompose the organic material present in the water [20].

b. Microbial metabolism: Microorganisms metabolize organic pollutants through aerobic or anaerobic processes, breaking them down into simpler, nontoxic compounds such as carbon dioxide, water, methane, and biomass [20].

c. Flocculation and sedimentation: In aerobic processes like activated sludge, microorganisms form flocs that aggregate and settle, allowing for the separation of treated water and microbial biomass [12].

2.2 Role of microorganisms in wastewater treatment

Microorganisms play a pivotal role in the biological treatment of sewage by facilitating the breakdown of organic matter and other pollutants [21].

a. Organic matter degradation: Bacteria, fungi, and protozoa consume organic pollutants, converting them into simpler compounds. Aerobic bacteria require oxygen to perform this process, while anaerobic bacteria thrive in oxygen-free environments.

b. Nutrient removal: Certain bacteria are capable of removing nutrients such as nitrogen and phosphorus from wastewater. Nitrifying bacteria convert ammonia into nitrate, which can then be further processed by denitrifying bacteria to produce nitrogen gas, reducing nutrient loads in the effluent.

c. Pathogen reduction: Some microorganisms can outcompete or consume pathogenic bacteria and viruses, contributing to the overall reduction of harmful pathogens in treated wastewater.

d. Biogas production: In anaerobic digestion, microorganisms decompose organic matter to produce biogas, primarily composed of methane and carbon dioxide, which can be captured and used as a renewable energy source.

e. Biofilm formation: In certain treatment systems like trickling filters and bio-towers, microorganisms form biofilms on the surfaces of the media. These biofilms facilitate the treatment process by providing a large surface area for microbial activity and organic matter degradation.

Comprehending the underlying principles and the pivotal functions of microorganisms is imperative for the efficient optimization and administration of biological sewage treatment procedures. The effective and ecologically sustainable design and operation of treatment systems are supported by this fundamental understanding.

3. Activated sludge process (aerobic treatment)

3.1 Overview of the activated sludge process

The activated sludge process is a widely used method in wastewater treatment that involves the use of aerobic microorganisms to decompose organic pollutants in sewage. In this process, wastewater is mixed with a microbial culture, known as activated sludge, in the presence of oxygen [22]. The microorganisms metabolize the organic matter, forming aggregates called flocs, which can be easily separated from the treated water [9]. Historically, the activated sludge process was developed in the early twentieth century by Edward Ardern and William Lockett in England. Their pioneering work in 1914 demonstrated that aerating sewage with microorganisms could effectively reduce organic pollutants [23]. Since then, the process has evolved and been widely adopted due to its efficiency and adaptability to various types of wastewaters [20].

3.2 Mechanisms of activated sludge

3.2.1 Microbial activity and organic matter degradation

The activated sludge process is a cornerstone of modern wastewater treatment, primarily driven by the metabolic activities of a diverse microbial consortium. The degradation of organic matter in this system involves a series of complex biochemical and microbial interactions, with aerobic bacteria playing a central role [24]. The microbial community within activated sludge is highly diverse, comprising bacteria, protozoa, fungi, and archaea [25]. Bacteria, particularly aerobic heterotrophs, are the most significant contributors to organic matter degradation [26]. Key bacterial genera include *Pseudomonas, Bacillus, Nitrosomonas*, and *Nitrobacter*, each participating in different stages of organic compound breakdown [27]. The process of organic matter degradation involves several interrelated biochemical pathways [28]. Initially, large organic polymers such as proteins, lipids, and polysaccharides are hydrolyzed by extracellular enzymes (proteases, lipases, and cellulases) into smaller monomers (amino acids, fatty acids, and sugars) [29, 30]. This crucial initial step renders the organic matter accessible to microbial uptake. Aerobic bacteria utilize oxygen as a terminal electron acceptor in their metabolic processes [31]. The monomers produced during hydrolysis are further oxidized through glycolysis, the tricarboxylic acid cycle, and oxidative phosphorylation, leading to the production of carbon dioxide, water, and energy in the form of adenosine triphosphate (ATP) [31, 32]. This energy is essential for microbial growth and maintenance [33]. Additionally, a fraction of the degraded organic matter is assimilated into new microbial biomass, which is critical for the sustenance and proliferation of the microbial community [33].

Several environmental parameters critically influence microbial activity and organic matter degradation efficiency in the activated sludge process. Sufficient dissolved oxygen (DO) levels are imperative for aerobic respiration [34]. Low DO can lead to the proliferation of facultative anaerobes and the onset of incomplete degradation pathways, resulting in suboptimal treatment performance [35]. The sludge retention time (SRT) or mean cell residence time (MCRT) dictates the time microorganisms remain in the system [36]. Optimal SRT ensures the retention of slow-growing but essential microbial species, enhancing overall degradation efficiency. Additionally, the enzymatic activity and microbial growth rates are pH and temperature-dependent, with optimal conditions typically ranging between pH 6.5–8.5 [37] and temperatures of 20–35°C [38], although specific microbes may thrive under different conditions.

To optimize organic matter degradation, several advanced strategies and technologies have been employed. Bioaugmentation involves the introduction of specialized microbial strains to bolster the degradation of specific contaminants or to enhance overall process stability [39]. Membrane bioreactors (MBRs) combine activated sludge with membrane filtration technology, allowing for higher biomass concentrations and improved effluent quality [40]. The implementation of real-time monitoring systems and automated control strategies helps maintain optimal environmental conditions and promptly address any process perturbations.

3.2.2 Formation and role of flocs

As the microorganisms metabolize the organic matter, they produce extracellular polymeric substances (EPS), which help in the aggregation of cells into flocs [41]. These flocs are dense clusters of bacteria, protozoa, and other microorganisms. The flocs have a higher settling rate, allowing them to be easily separated from the treated water during the sedimentation stage. The settled flocs, known as sludge, can be recycled back into the aeration tank to maintain a high concentration of microorganisms or removed for further treatment [15].

3.3 Process configuration

3.3.1 Components of activated sludge systems

An activated sludge system typically comprises several key components essential for the efficient treatment of wastewater. As shown in **Table 1**, these components

Components	Description
Aeration tank	Where wastewater is mixed with activated sludge and aerated to provide oxygen for microbial activity.
Sedimentation tank (Clarifier)	Where the flocs settle, separating the treated water from the sludge.
Sludge recycling system	Which returns a portion of the settled sludge to the aeration tank to maintain microbial concentration.
Sludge disposal system	For handling excess sludge that is not recycled.

Table 1.
Description of components of activated sludge system.

include the aeration tank, where wastewater is mixed with microbial biomass and aerated to promote the breakdown of organic matter. Following this, the mixture flows into a sedimentation tank, also known as a secondary clarifier, where the activated sludge settles out, separating from the treated effluent [39].

3.3.2 Process flow and stages

The operations of the flow process include pretreatment, aeration, sedimentation, disinfection, and sludge handling (**Table 2**). The activated sludge system is a widely used process in wastewater treatment, involving several key stages and operations. It begins with the primary treatment, where large solids are removed from the wastewater. The primary effluent then enters an aeration tank, where it is mixed with a microbial biomass called activated sludge. Oxygen is supplied to the tank through aerators to support the aerobic microorganisms that decompose organic matter [29]. The mixture then flows to a secondary clarifier, where the activated sludge settles out, and the treated effluent is separated and discharged. A portion of the settled sludge, known as return-activated sludge, is recirculated back to the aeration tank to maintain the microbial population. The excess sludge, or waste-activated sludge, is removed for further treatment or disposal. This continuous cycle ensures the efficient breakdown of organic pollutants and the production of clean effluent [15].

3.4 Benefits and limitations

The sludge system offers several advantages. It is effective in removing organic matter, nutrients, and pathogens from wastewater, resulting in relatively high-quality

Process	Operations
Pretreatment	Removal of large solids and grit to protect downstream processes.
Aeration	Mixing wastewater with activated sludge and supplying oxygen.
Sedimentation	Settling of flocs in a clarifier to separate treated water from sludge.
Disinfection	This is an optional further treatment to kill the remaining pathogens.
Sludge handling	Recycling and disposal of settled sludge.

Table 2.
Flow process and operations of activated sludge system.

effluent [35]. The process is also adaptable to various scales, from small community systems to large municipal plants [37]. Furthermore, it produces biogas during anaerobic digestion, which can be used as a renewable energy source, contributing to energy savings and sustainability. Additionally, the treated sludge can be utilized as a fertilizer or soil conditioner, promoting resource recovery and reducing waste disposal needs [38].

However, the sludge system also has notable disadvantages. The initial setup and maintenance costs can be high, requiring significant investment in infrastructure and skilled personnel. The process generates large volumes of sludge, which necessitates proper handling, treatment, and disposal, posing environmental and logistical challenges. There is also a risk of odor and potential health hazards if the sludge is not adequately managed [20]. Moreover, the system can be energy-intensive, particularly in the aeration stages, leading to increased operational costs and carbon footprint [12]. Lastly, regulatory compliance and monitoring requirements can be stringent, adding to the complexity and cost of managing sludge systems effectively.

4. Anaerobic digestion process

4.1 Overview of anaerobic digestion

Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen. This process results in the production of biogas, primarily composed of methane and carbon dioxide, and a nutrient-rich digestate. Anaerobic digestion is commonly used for treating high-strength wastewater and organic solid wastes, including sewage sludge, agricultural residues, and industrial effluents [20]. Historically, the use of anaerobic digestion dates back to ancient times, with early civilizations employing rudimentary methods to treat organic waste. The modern development of anaerobic digestion began in the nineteenth century, with significant advancements in understanding microbial processes and reactor designs. The first full-scale anaerobic digester was built in 1859 in Bombay, India. Since then, the technology has evolved, with widespread applications in wastewater treatment, renewable energy production, and waste management [4].

4.2 Mechanisms of anaerobic digestion

4.2.1 Microbial activity and organic matter degradation

Anaerobic digestion involves a series of microbial processes that convert complex organic matter into simpler compounds [12, 42]. The process occurs in four main stages shown in **Figure 1**

a. Hydrolysis: Complex organic molecules such as carbohydrates, proteins, and fats are broken down into simpler sugars, amino acids, and fatty acids.

b. Acidogenesis: The products of hydrolysis are further converted into volatile fatty acids, alcohols, hydrogen, and carbon dioxide by acidogenic bacteria.

c. Acetogenesis: Acidogenic intermediates are converted into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria.

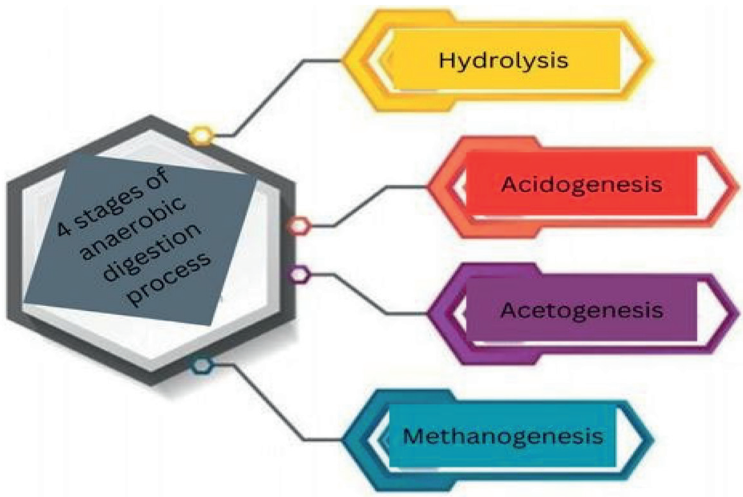

Figure 1.
Anaerobic processes in organic matter degradation.

d. Methanogenesis: Methanogenic archaea produce methane and carbon dioxide from acetic acid, hydrogen, and carbon dioxide.

4.2.2 Production of biogas

Biogas is a valuable by-product of anaerobic digestion, consisting mainly of methane (CH_4) and carbon dioxide (CO_2), with trace amounts of other gases such as hydrogen sulfide (H_2S). Methane, a potent greenhouse gas, can be captured and utilized as a renewable energy source for electricity generation, heating, or as a vehicle fuel. The production of biogas not only provides an alternative energy source but also helps reduce greenhouse gas emissions [43, 44].

4.3 Process configuration

4.3.1 Components and stages of anaerobic digestion systems

As shown in **Table 3**, aerobic digestion systems involve the breakdown of organic matter in the presence of oxygen by aerobic microorganisms. These systems typically include components such as aeration tanks, where oxygen is supplied to the microbial community to facilitate the decomposition process, and secondary clarifiers, where solids are separated from the treated effluent. The process includes stages like initial aeration, where organic matter is rapidly broken down, followed by stabilization, where further decomposition reduces the volume and mass of the sludge. The end products of aerobic digestion are carbon dioxide, water, and a stabilized sludge that can be used as a soil amendment or disposed of safely [43].

4.4 Operational parameters

Figure 2 highlights several factors that influence the efficiency of anaerobic digestion.

Components	**Description**
a. Digester Tank	A sealed, oxygen-free container where the anaerobic digestion process occurs.
b. Feedstock Storage and Preparation	Facilities for storing and preparing organic waste materials before feeding them into the digester.
c. Biogas Collection and Storage	Systems for capturing and storing the produced biogas.
d. Digestate Storage and Handling	Facilities for handling the nutrient-rich digestate, which can be used as fertilizer or soil amendment.
Flow process stages	**Operations**
a. Feedstock Preparation	Organic waste is collected, sorted, and pre-treated to enhance its biodegradability.
b. Digestion	The feedstock is deposited in a digester tank, where anaerobic microorganisms break down the organic matter over several weeks.
c. Biogas Collection	The produced biogas is collected from the top of the digester tank and stored for further use.
d. Digestate Handling	The remaining digestate is removed from the digester, stored, and eventually used as a fertilizer or soil conditioner.

Table 3.
Description of aerobic digestion system.

Figure 2.
Factors that influence anaerobic digestion.

Temperature is a critical factor influencing the rate and efficiency of anaerobic digestion, which can occur under three temperature ranges: psychrophilic (below 20°C, with a slow digestion rate), mesophilic (20–45°C, the optimal range for most digesters, typically around 35°C), and thermophilic (45–60°C, with a higher digestion

Benefits	Limitations and Challenges
Renewable Energy Production: Generates biogas that can be used as a sustainable energy source.	High Capital Costs: Initial investment for anaerobic digestion systems can be substantial.
Reduction of Waste Volume: Significantly reduces the volume of organic waste, minimizing disposal requirements. **Nutrient Recovery**: Produces nutrient-rich digestate that can be used as fertilizer, enhancing soil health and agricultural productivity.	Technical Complexity: Requires careful monitoring and control of operational parameters to ensure stable performance. Sensitivity to Environmental Conditions: Microbial activity can be affected by fluctuations in temperature, pH, and substrate composition.
Greenhouse Gas Mitigation: Captures methane that would otherwise be released into the atmosphere, reducing greenhouse gas emissions.	Potential for Toxic Compounds: Certain feedstocks may contain substances that inhibit microbial activity, requiring pretreatment or careful management.
Odor Control: Reduces odors associated with organic waste decomposition.	

Table 4.
Benefits and limitations of anaerobic digestion.

rate but more energy-intensive) [45]. The pH of the digestion environment affects microbial activity and process stability, with an optimal range between 6.5 and 8.0, and maintaining pH within this range is essential to prevent the inhibition of microbial processes [46]. The concentration of organic matter (substrate) in the feedstock impacts the digestion process, where high substrate concentrations can lead to rapid biogas production but may also cause system overload and process instability, thus balancing substrate concentration is crucial for maintaining stable operation [47]. Retention time, which refers to the duration that the feedstock remains in the digester, ensures complete digestion of organic matter and optimal biogas production, with typical retention times ranging from 15 to 30 days, depending on the feedstock and operating conditions [48].

4.5 Benefits and limitations of anaerobic digestion

Anaerobic digestion offers several benefits, including the production of biogas, a renewable energy source that can be used for electricity and heat, thus reducing reliance on fossil fuels. It also produces a nutrient-rich digestate that can be used as a fertilizer, enhancing soil health [45]. Additionally, anaerobic digestion helps in reducing greenhouse gas emissions and managing organic waste more effectively. However, it has limitations, such as the need for careful monitoring and control of the digestion process, high initial setup costs, and the potential for odor issues [46]. Furthermore, the efficiency of the process can be affected by the variability in feedstock composition and the need for pretreatment in some cases (see **Table 4**).

From the highlights of the benefits and limitations, notably, optimizing anaerobic digestion for effective waste treatment and resource recovery requires a thorough understanding of its principles and operating parameters.

5. Comparative analysis of aerobic and anaerobic processes

The distinct properties of the aerobic and anaerobic processes are succinctly highlighted.

5.1 Efficiency in organic matter removal

In aerobic processes, activated sludge processes, like those used in wastewater treatment, can efficiently remove up to 95% of Biochemical Oxygen Demand (BOD) due to the rapid metabolism of aerobic microorganisms. However, anaerobic digestion effectively reduces organic matter in wastewater, removing 50–70% of chemical oxygen demand (COD), but is slower due to lower metabolic rates of microorganisms.

5.2 Energy requirements and production

Large-scale systems require significant energy input for aeration to maintain oxygen levels for aerobic microorganisms, which can be a significant operational cost. However, anaerobic digestion, a process without aeration, offers lower energy requirements and biogas production, which can be used as a renewable energy source or surplus energy [49].

5.3 Environmental impact

Aerobic processes produce less odor and reduce organic pollutants, but their high energy demand, often from nonrenewable sources, can increase their carbon footprint. Biogas production reduces fossil fuel reliance and promotes renewable energy. Digestate can be used as fertilizer, promoting nutrient recycling. Drawbacks include methane emissions and odor issues [50].

5.4 Application scenarios

For aerobic processes, the high efficiency wastewater treatment system is ideal for municipal applications requiring quick processing times and low energy costs, aiming to meet stringent discharge standards and improve water quality [51]. However, in anaerobic, the product is ideal for high-strength industrial wastewater, agricultural wastes, and sewage sludge with high organic loads, particularly in scenarios requiring energy recovery and waste stabilization, especially in rural or decentralized locations [52].

As comparatively outlined, selecting the best treatment option depends on several factors, including the characteristics of the wastewater, operational objectives, and environmental concerns. It is helpful to understand the relative benefits and drawbacks of aerobic and anaerobic processes.

6. Factors influencing performance

6.1 Environmental conditions

6.1.1 Temperature

For Aerobic Processes, optimal microbial activity typically occurs within the mesophilic range (15–35°C). Higher temperatures can enhance reaction rates but may lead to increased energy consumption for aeration. Conversely, lower temperatures can slow down microbial metabolism, reducing treatment efficiency. However, Anaerobic digestion can operate under psychrophilic (below 20°C), mesophilic (20–45°C), and thermophilic (45–60°C) conditions. Mesophilic and thermophilic conditions are preferred for their higher biogas production rates and better pathogen reduction, though thermophilic digestion requires more energy input for heating [45].

6.1.2 pH levels

For Aerobic Processes, the optimal pH for aerobic treatment is generally between 6.5 and 8.5. Deviation from this range can inhibit microbial activity and reduce the efficiency of organic matter degradation [53]. However, anaerobic digestion performs best within a pH range of 6.5–8.0. Maintaining a stable pH is critical, as acidic conditions (pH below 6.5) can inhibit methanogenic bacteria, while alkaline conditions (pH above 8.0) can negatively affect other microbial communities involved in the digestion process [54].

6.2 Wastewater composition

6.2.1 Organic load

For Aerobic Processes, high organic loads can enhance microbial growth and activity but may also lead to issues like sludge bulking and poor settling if not properly managed. Balancing the organic load is crucial for maintaining system stability and efficiency. Similarly, Anaerobic digestion is particularly effective for high-strength wastewaters with high organic loads. However, excessive organic loading can lead to process instability, accumulation of volatile fatty acids, and inhibition of methanogenesis [53].

6.2.2 Presence of inhibitors

For Aerobic Processes, toxic compounds, such as heavy metals, pesticides, and industrial chemicals, can inhibit microbial activity and reduce treatment efficiency. Pretreatment of wastewater to remove or neutralize inhibitors may be necessary [55]. Similarly, Anaerobic microorganisms are sensitive to inhibitors like ammonia, sulfides, and certain organic compounds. High concentrations of these substances can disrupt microbial communities and biogas production. Monitoring and managing inhibitor levels are essential for stable operation [56].

6.3 System design and operation

6.3.1 Reactor design

In Aerobic Processes, common reactor designs include completely mixed aeration tanks, plug flow reactors, and sequencing batch reactors. The choice of design influences oxygen transfer efficiency, mixing, and overall treatment performance. Proper design ensures effective contact between microorganisms and organic matter [45]. However, Anaerobic digesters come in various designs, such as continuously stirred tank reactors (CSTRs), up-flow anaerobic sludge blanket (UASB) reactors, and anaerobic sequencing batch reactors. Design considerations include retention time, mixing, and biogas collection efficiency to optimize digestion performance [55].

6.3.2 Operational practices

Aerobic Processes' effective operational practices include maintaining appropriate dissolved oxygen levels, regular monitoring of sludge age and concentration, and periodic removal of excess sludge [28]. Consistent monitoring and control of operational parameters ensure optimal microbial activity and treatment efficiency. However, anaerobic processes' key operational practices involve maintaining stable temperature and pH, regular feeding of substrates, and effective management of biogas production and digestate disposal [57]. Monitoring parameters like volatile fatty acid concentration, alkalinity, and biogas composition helps in maintaining stable digestion processes.

To ensure effective pollutant removal, achieve stable and sustainable operation, and maximize the performance of both aerobic and anaerobic sewage treatment processes, it is imperative to comprehend and manage these aspects.

7. Recent advancements in biological sewage treatment

7.1 New microbial strains

7.1.1 Development and application

a. Genetic engineering: Advances in genetic engineering have enabled the development of microbial strains with enhanced capabilities for degrading specific pollutants, increasing treatment efficiency. These genetically modified microorganisms can target hard-to-degrade compounds such as pharmaceuticals and industrial chemicals, offering improved performance in both aerobic and anaerobic processes [58, 59].

b. Bioaugmentation: The introduction of specialized microbial strains to wastewater treatment systems, known as bioaugmentation, can enhance the breakdown of specific contaminants and improve overall system performance. This approach has been particularly effective in treating industrial wastewater with high concentrations of recalcitrant compounds [39].

c. Consortia of microbes: Research has focused on creating microbial consortia, where multiple strains work synergistically to degrade complex organic matter more efficiently [60]. These consortia are designed to exploit the complementary metabolic pathways of different microorganisms, resulting in more robust and resilient treatment processes [24].

d. Adaptation to extreme conditions: Microbial strains that can thrive under extreme conditions, such as high salinity, low pH, or high temperatures, have been developed [60]. These strains expand the applicability of biological treatment to a wider range of wastewater, including those from specific industrial sectors or regions with harsh climates [61].

7.2 Hybrid treatment systems

7.2.1 Combination of aerobic and anaerobic processes

a. Integrated systems: Hybrid treatment systems combine aerobic and anaerobic processes to leverage the advantages of both methods. For instance, an anaerobic digester can first reduce the organic load and produce biogas, followed by an aerobic treatment to polish the effluent and achieve higher water quality standards [62].

b. Sequential reactors: In these systems, wastewater undergoes sequential treatment in separate anaerobic and aerobic reactors. This configuration allows for the phased removal of different types of pollutants, optimizing overall treatment efficiency [63].

c. Simultaneous processes: Some hybrid systems integrate both aerobic and anaerobic processes within a single reactor, creating distinct zones for each process. This approach can enhance nutrient removal and reduce the footprint of treatment facilities [64].

7.3 Benefits and challenges

7.3.1 Benefits

a. Enhanced treatment efficiency: Combining aerobic and anaerobic processes can achieve higher overall pollutant removal rates, including more effective degradation of complex organic compounds and nutrients.

b. Energy optimization: Anaerobic digestion can reduce the organic load and produce biogas, which can be used to power aerobic treatment systems, offsetting energy costs.

c. Improved sludge management: Hybrid systems can reduce the volume and improve the stability of sludge, making it easier to handle and dispose of.

d. Flexibility and resilience: The integration of both processes can provide greater operational flexibility and resilience to fluctuating wastewater characteristics and loads.

7.3.2 Challenges

a. The complexity of design and operation: Hybrid systems require careful design and precise control of operational parameters to ensure that both aerobic and anaerobic processes function optimally. This complexity can increase capital and operational costs.

b. Integration issues: Ensuring seamless integration between aerobic and anaerobic stages can be challenging, particularly in maintaining appropriate environmental conditions for each process.

c. Balancing microbial communities: Maintaining balanced and healthy microbial communities in both aerobic and anaerobic zones is critical for consistent performance. Disruptions in one part of the system can impact the overall treatment efficiency.

d. Monitoring and control: Hybrid systems require advanced monitoring and control systems to manage the interactions between aerobic and anaerobic processes, detect potential issues, and optimize performance.

Therefore, the efficiency, adaptability, and sustainability of biological sewage treatment have been significantly improved by recent developments in microbial technology and hybrid treatment systems. In a world that is changing quickly, these technologies have the potential to address the mounting problems associated with wastewater management.

8. Conclusion

Biological treatment techniques play a crucial role in sewage management, focusing on the core principles, mechanisms, and applications of aerobic and anaerobic processes. The activated sludge process is noted for its high efficiency and adaptability, while anaerobic digestion is recognized for its energy recovery and waste volume reduction benefits. Both methods have their distinct advantages and face unique challenges, influenced significantly by factors such as environmental conditions, wastewater composition, and system design. Recent advancements, such as the development of new microbial strains and hybrid treatment systems, have further enhanced the effectiveness and sustainability of biological sewage treatment. These innovations are essential for addressing the evolving challenges in wastewater management, ultimately improving public health and environmental protection.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Ernest Mbamalu Ezeh[1*], Peter Chinedu Agu[2] and Epere Aworabhi[1]

1 Faculty of Engineering, Department of Chemical Engineering, Federal University, Otuoke, Nigeria

2 Department of Biochemistry, College of Science, Evangel University, Akaeze, Nigeria

*Address all correspondence to: ezehem@fuotuoke.edu.ng

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