

Water Reclamation

Water Reclamation:

An Exploration into Utilising Wastewater

Edited by

Reena Roy and Wajid Hasan

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BIOLOGICAL WASTEWATER TREATMENT

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Abstract

The chapter presents a comprehensive overview that delves into the realm of biological wastewater treatment, exploring its fundamental principles, advanced technologies, emerging trends, and policy implications. Beginning with an introduction to the significance of biological processes in wastewater treatment, the discussion navigates through historical perspectives and basic principles, setting the stage for a deeper exploration. The microbiology of wastewater treatment is scrutinized next, focusing on microbial diversity and the pivotal role microorganisms play in treatment processes. Key microbial processes, encompassing aerobic and anaerobic mechanisms, are elucidated, shedding light on the intricate microbial ecology within treatment systems. The discourse then transitions into an examination of various biological treatment processes, including the activated sludge process, trickling filters, rotating biological contactors, and anaerobic digestion. Each process is dissected, offering insights into its configuration, operation, performance evaluation, and application domains. As the narrative unfolds, attention shifts towards advanced biological treatment technologies such as membrane bioreactors and sequencing batch reactors. These technologies, characterized by their innovative design, operational flexibility, and superior treatment efficiency, represent promising avenues for future wastewater treatment endeavors. Emerging trends and future directions in wastewater treatment are explored next, highlighting the integration of biological and physicochemical processes, resource recovery initiatives, the application of artificial intelligence in process control, and the embrace of sustainability and circular economy

principles. The discussion culminates in an analysis of challenges and opportunities in the field, addressing issues related to emerging contaminants, regulatory frameworks, technological innovations, and future research directions. Recommendations for further reading and resources are provided, offering readers a pathway to delve deeper into the multifaceted realm of biological wastewater treatment. This overview encapsulates the multifaceted landscape of biological wastewater treatment, offering insights into its significance, challenges, innovations, and prospects. Through a holistic understanding of these dynamics, stakeholders can navigate the complexities of wastewater management with clarity and purpose.

Keywords: Wastewater treatment, Advanced technology, Challenges, Sustainability

Introduction

Throughout history, various civilizations have implemented rudimentary methods to dispose of wastewater, ranging from simple drainage systems to the direct discharge of untreated sewage into water bodies. These early practices were primarily aimed at removing wastewater from populated areas to prevent foul odors and disease outbreaks. The Industrial Revolution brought about significant advancements in wastewater treatment, driven by the need to address the growing pollution concerns associated with urbanization and industrialization. In the late 19th and early 20th centuries, the development of sewage systems and centralized treatment plants marked the beginning of modern wastewater treatment practices (Mittal, 2011).

The understanding of microbiology and microbial metabolism in the early 20th century laid the foundation for the development of biological wastewater treatment processes. Pioneering work by researchers such as Edward Ardern and William Lockett in the UK led to the invention of the activated sludge process, a landmark achievement in the field of wastewater treatment. Subsequent innovations, including trickling filters, anaerobic digestion, and biological nutrient removal, further expanded the repertoire of biological treatment options. Biological wastewater treatment is a process that utilizes microorganisms to degrade organic matter and remove pollutants from wastewater (Wei *et al.*, 2003). This method harnesses the natural abilities of microorganisms to break down complex organic compounds into simpler, more stable forms, thereby rendering the wastewater less harmful to the environment.

Biological wastewater treatment plays a crucial role in safeguarding public health and protecting the environment. Removing organic pollutants, nutrients, and pathogens from wastewater helps prevent the contamination of surface water bodies, groundwater sources, and drinking water supplies. Moreover, biological treatment facilitates the reuse and recycling of water, promoting sustainable water management practices. Additionally, compliance with regulatory standards for wastewater discharge is essential to mitigate adverse impacts on ecosystems and human health. Biological wastewater treatment processes harness the metabolic activities of microorganisms to degrade organic pollutants and remove contaminants from wastewater (Lettinga, 1996; Wei *et al.*, 2003). These processes can be broadly categorized into aerobic and anaerobic pathways, depending on the availability of oxygen. Several factors influence the performance of biological treatment systems, including temperature, pH, dissolved oxygen levels, hydraulic retention time, and nutrient availability. Optimal operating conditions are essential to maintain the activity and growth of microbial communities responsible for wastewater treatment.

The effectiveness of biological treatment is typically assessed based on various performance metrics, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and nutrient concentrations. Effluent quality standards set by regulatory agencies dictate the permissible limits for these parameters to ensure compliance with environmental regulations and protect receiving water bodies (Vanhooren *et al.*, 2003).

Microbiology of Wastewater Treatment

A. Microbial Diversity

Microorganisms play a vital role in the treatment of wastewater due to their diverse metabolic capabilities and adaptive traits. The microbial community present in wastewater treatment systems comprises a wide array of bacteria, archaea, fungi, protozoa, and viruses. These microorganisms interact synergistically to degrade organic matter, remove nutrients, and stabilize the treatment process (Unz, 1975).

Bacteria are the primary drivers of biological processes in wastewater treatment, encompassing various genera and species with distinct metabolic pathways. Aerobic bacteria such as *Pseudomonas*, *Aeromonas*, and *Acinetobacter* are responsible for oxidizing organic compounds to produce energy and biomass. Anaerobic bacteria like *Methanosaeta* and

Methanosarcina facilitate the conversion of organic matter into methane gas through fermentation and methanogenesis. Archaea, particularly methanogenic archaea such as Methanobacterium and Methanosarcina, play a crucial role in anaerobic digestion processes by converting volatile fatty acids and hydrogen into methane. Fungi contribute to the degradation of complex organic polymers, including lignin and cellulose, through extracellular enzymatic activities, thereby enhancing the efficiency of organic matter removal in wastewater treatment systems (Pipes, 1980). Protozoa, including ciliates, amoebae, and flagellates, serve as grazers in wastewater treatment systems, preying on bacteria and contributing to the removal of suspended solids and pathogens. Viruses, although not actively involved in metabolic processes, pose a potential risk of infecting host organisms and causing waterborne diseases if not effectively removed during treatment.

B. Role of Microorganisms in Wastewater Treatment

The primary function of microorganisms in wastewater treatment is the degradation of organic matter present in sewage and industrial effluents. Aerobic bacteria utilize oxygen to oxidize organic compounds into simpler byproducts such as carbon dioxide and water, while anaerobic bacteria break down organic matter in the absence of oxygen, yielding methane and carbon dioxide.

Microorganisms are also involved in the removal of nutrients, including nitrogen and phosphorus, from wastewater through biological processes such as nitrification, denitrification, and phosphorus uptake. Nitrifying bacteria like Nitrosomonas and Nitrobacter oxidize ammonia to nitrite and nitrate while denitrifying bacteria such as Paracoccus and Pseudomonas reduce nitrate to nitrogen gas under anaerobic conditions. Phosphorus-accumulating organisms (PAOs) and polyphosphate-accumulating organisms (PAOs) assimilate phosphorus into their cells, thereby reducing its concentration in the effluent. Microorganisms contribute to the reduction of pathogenic bacteria, viruses, and protozoa in wastewater through predation, competition, and inactivation mechanisms (Daims *et al.*, 2006). Protozoan predators like amoebae and flagellates feed on pathogenic bacteria, while viruses may undergo physical or chemical inactivation during wastewater treatment processes such as disinfection.

In anaerobic digestion processes, microorganisms play a key role in stabilizing organic sludge by converting volatile solids into methane gas and residual biomass. Methanogenic archaea facilitate the breakdown of

complex organic compounds, while syntrophic bacteria form symbiotic relationships with methanogens to degrade fatty acids and other intermediates.

Key Microbial Processes in Wastewater Treatment

Aerobic Processes

Aerobic processes in wastewater treatment rely on the presence of oxygen to facilitate the degradation of organic pollutants and the removal of nutrients. These processes occur in aerobic environments where dissolved oxygen is available to support microbial metabolism (Xu *et al.*, 2021).

Aerobic bacteria utilize oxygen as a terminal electron acceptor to oxidize organic compounds present in wastewater. Through enzymatic reactions, bacteria break down complex organic molecules into simpler byproducts such as carbon dioxide, water, and biomass (Xi *et al.*, 2022). This process, known as aerobic respiration, releases energy that bacteria use for growth and reproduction.

Nitrification is the biological oxidation of ammonia (NH_3) to nitrite (NO_2^-) and then to nitrate (NO_3^-). This process is carried out by two groups of autotrophic bacteria: ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). AOB, such as *Nitrosomonas* and *Nitrospira*, convert ammonia to nitrite, while NOB, such as *Nitrobacter* and *Nitrospira*, further oxidize nitrite to nitrate. Nitrification plays a crucial role in nitrogen removal from wastewater, particularly in treating effluents high in ammonia concentrations. Aerobic denitrification is a recently discovered process where certain bacteria are capable of reducing nitrate (NO_3^-) to nitrogen gas (N_2) under aerobic conditions. This process offers an alternative to conventional anaerobic denitrification and can occur in oxygen-rich environments. Aerobic denitrifiers, such as *Paracoccus denitrificans* and *Pseudomonas stutzeri*, use nitrate as an electron acceptor for respiratory metabolism, producing nitrogen gas as a byproduct (Chen *et al.*, 2017; Nancharaiiah & Sarvajith, 2019; Sanjeevi, 2011). Some bacteria can accumulate phosphorus intracellularly in the form of polyphosphate, which can be removed from wastewater during biomass separation. These phosphorus-accumulating organisms (PAOs), such as *Candidatus Accumulibacter* and *Tetrasphaera*, assimilate orthophosphate (PO_4^{3-}) into their cells and store it as polyphosphate granules. Biological phosphorus removal is typically achieved in sequencing batch reactors (SBRs) or anaerobic-anoxic-oxic (A_2O) systems, where alternating aerobic and

anaerobic conditions promote the uptake and release of phosphorus by PAOs.

Anaerobic Processes

Anaerobic processes in wastewater treatment occur in the absence of oxygen and rely on alternative electron acceptors, such as nitrate, sulfate, and carbon dioxide, for microbial metabolism. These processes are particularly important for treating high-strength organic wastes and generating renewable energy in the form of biogas (Van Lier *et al.*, 2008).

Anaerobic digestion is a microbial process where complex organic compounds are converted into methane (CH_4) and carbon dioxide (CO_2) by a consortium of anaerobic bacteria and archaea. Four stages characterize anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolytic bacteria break down complex polymers into simpler molecules, which are then fermented by acidogenic bacteria to produce volatile fatty acids (VFAs) and hydrogen (H_2). Acetogenic bacteria further convert VFAs into acetate, hydrogen, and carbon dioxide, which serve as substrates for methanogenic archaea to produce methane. Anammox is a biological process where ammonia (NH_3) is oxidized directly to nitrogen gas (N_2) using nitrite (NO_2^-) as the electron acceptor under anaerobic conditions. This process is carried out by a group of chemolithoautotrophic bacteria known as anammox bacteria, such as *Candidatus Kuenenia* and *Candidatus Brocadia*. Anammox bacteria perform the anammox reaction in specialized intracellular compartments called anammoxosomes, utilizing hydrazine (N_2H_4) as an intermediate to generate nitrogen gas. Sulfate-reducing bacteria (SRB) are anaerobic microorganisms that utilize sulfate (SO_4^{2-}) as a terminal electron acceptor for anaerobic respiration. SRBs, such as *Desulfovibrio* and *Desulfobacter*, reduce sulfate to hydrogen sulfide (H_2S) through a series of enzymatic reactions. Sulfate reduction plays a role in sulfur cycling and can contribute to the removal of sulfate and metal ions from wastewater through precipitation and biological sulfide production (Narihiro & Sekiguchi, 2007; Stronach *et al.*, 2012). Methanogenesis is the final stage of anaerobic digestion, where methanogenic archaea produce methane from acetate, hydrogen, and carbon dioxide generated during the preceding fermentation and acetogenesis stages. Methanogens are strict anaerobes and belong to the phylum Euryarchaeota, encompassing genera such as *Methanosaeta*, *Methanosarcina*, and *Methanobacterium*. Methane produced by methanogenic archaea can be captured and utilized as a renewable energy

source, contributing to the sustainability of anaerobic wastewater treatment processes.

Biological Treatment Processes

A. Activated Sludge Process

The activated sludge process is one of the most widely used biological treatment methods for municipal and industrial wastewater. It involves the aerobic treatment of wastewater in a suspended growth system, where microorganisms are kept in suspension and continuously aerated to facilitate the degradation of organic pollutants (Abbasi, Sanjeevi, *et al.*, 2013; Wang *et al.*, 2009). This chapter provides an overview of the activated sludge process, including its process description, kinetics, and design considerations.

The activated sludge process typically consists of the following unit operations:

Wastewater enters the aeration tank, where it is mixed with recycled sludge (return-activated sludge) and supplied with oxygen through diffusers or mechanical aerators. The dissolved oxygen supports the growth and activity of aerobic microorganisms, which metabolize organic matter present in the wastewater. After the aeration phase, the mixed liquor containing suspended microorganisms and treated wastewater flows into the clarifier, where gravity settles the biomass, forming a sludge blanket at the bottom. Treated effluent is collected from the top of the clarifier and discharged for further treatment or disposal (Wu *et al.*, 2016). A portion of the settled sludge, known as return activated sludge (RAS), is recycled back to the aeration tank to maintain the desired biomass concentration and ensure treatment efficiency. Excess sludge is wasted from the system to prevent the accumulation of solids and maintain stable operation. The kinetics of the activated sludge process describe the rate of microbial growth and substrate utilization, which are influenced by factors such as substrate concentration, biomass concentration, and environmental conditions. Key kinetic parameters include: The Monod equation describes the relationship between the specific growth rate of microorganisms (μ) and the substrate concentration (S) in the wastewater (Ahansazan *et al.*, 2014; Ranjan *et al.*, n.d.). It is expressed as $\mu = \mu_{\max} * (S / (K_s + S))$, where μ_{\max} is the maximum specific growth rate and K_s is the substrate half-saturation constant. The oxygen uptake rate represents the rate at which microorganisms consume oxygen for metabolic activities, such as substrate

oxidation and biomass synthesis. This is often used to monitor and control the aeration process in activated sludge systems, ensuring adequate oxygen supply for microbial growth.

Designing an activated sludge system requires careful consideration of various factors to achieve optimal performance and meet effluent quality objectives. Key design considerations include:

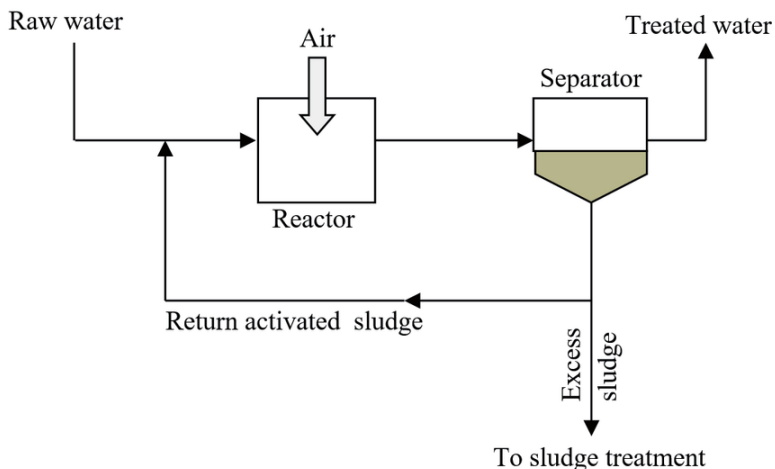


Figure 1. Activated Sludge Process

The HRT determines the average time wastewater spends in the aeration tank and influences the extent of treatment. Longer HRTs allow for more thorough degradation of organic matter and nutrient removal but may require larger reactor volumes. MLSS concentration reflects the biomass density in the aeration tank and affects treatment efficiency and settling characteristics. Proper MLSS control is essential to maintain stable operation and prevent bulking or foaming issues. The selection and design of aeration equipment play a critical role in providing adequate oxygen transfer to support microbial activity. Factors such as diffuser type, aeration rate, and oxygen transfer efficiency should be optimized to achieve uniform mixing and oxygen distribution throughout the reactor. Proper management of sludge wasting ensures the removal of excess biomass and maintains a healthy microbial population in the activated sludge system (Abbasi *et al.*, 2016; Barnard, 1976). The wasting rate should be adjusted based on biomass growth rates, solids retention time (SRT), and process stability.

B. Trickling Filters

Trickling filters are a widely used biological treatment technology for wastewater treatment, particularly in small to medium-sized municipal and industrial applications. This chapter explores the principle of operation, types of media used, and methods for performance evaluation of trickling filters. Trickling filters operate on the principle of biofilm growth, where microorganisms attach to a fixed media surface and form a thin layer of biomass. Wastewater is distributed over the media surface, either intermittently or continuously, allowing it to trickle through the biofilm layer (Naz *et al.*, 2015). As the wastewater passes through the biofilm, organic pollutants are degraded by aerobic microorganisms present in the biofilm, resulting in the removal of organic matter, nutrients, and pathogens.

The media bed provides a surface for biofilm attachment and supports the growth of microorganisms. Common media materials include plastic, rock, gravel, and synthetic materials with high surface area and porosity. Wastewater is evenly distributed over the media surface using distribution arms, spray nozzles, or rotating distributors. Uniform distribution ensures optimal contact between the wastewater and the biofilm, promoting efficient pollutant removal (Díez-Montero *et al.*, 2019; Kornaros & Lyberatos, 2006). A network of underdrains collects treated effluent from the bottom of the trickling filter and transports it to downstream treatment processes or discharge points. Underdrains may be equipped with filter media to further polish the effluent and remove any remaining solids.

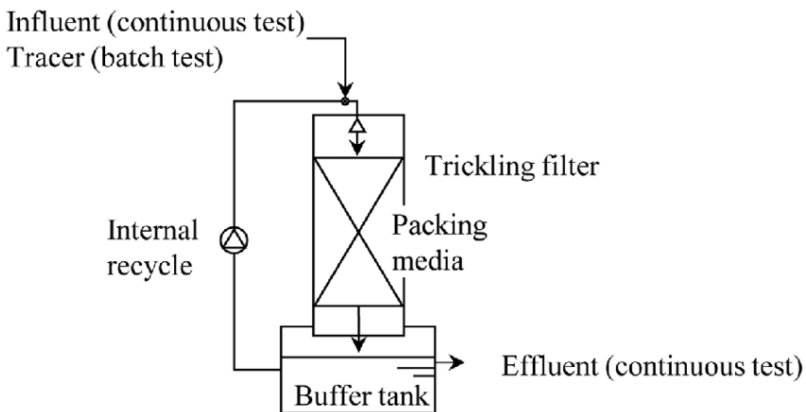


Figure 2. Trickling Filters

Trickling filters employ various types of media to provide a suitable habitat for biofilm growth and maximize treatment efficiency. Commonly used media types include: Natural rock or stone media, such as crushed rock, gravel, or slag, which are commonly used in traditional trickling filter systems. These media provide a high surface area for biofilm attachment and have excellent hydraulic characteristics for wastewater distribution. Plastic media, including structured plastic media and random packing media, offer enhanced surface area and porosity compared to traditional rock media. Structured plastic media feature intricate geometric shapes and configurations designed to maximize biofilm attachment and wastewater contact. Synthetic media materials, such as textile-based media or foam matrices, provide a lightweight and durable alternative to traditional media types (Abbasi *et al.*, 2012; Dhokpande *et al.*, 2014). These materials offer flexibility in design and installation and can be tailored to specific treatment requirements. Performance evaluation of trickling filters involves assessing key operational parameters, effluent quality, and treatment efficiency. Common methods for performance evaluation include:

The removal efficiency of trickling filters is typically determined by measuring influent and effluent concentrations of target pollutants, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and ammonia nitrogen ($\text{NH}_3\text{-N}$). Removal efficiencies are calculated based on mass balance equations and expressed as percentage removal. HLR represents the volume of wastewater applied to the trickling filter per unit area of media surface per unit of time. Optimal HLRs depend on media characteristics, hydraulic design, and treatment objectives and are typically determined through pilot-scale studies or hydraulic modeling. Biofilm thickness and biomass activity are indicators of microbial activity and treatment performance in trickling filters. These parameters can be assessed through microscopy, biomass sampling, and biofilm thickness measurements to monitor the health and activity of the microbial community. Monitoring operational parameters, such as hydraulic residence time (HRT), media clogging, and air-to-media ratio, is essential for optimizing trickling filter performance and preventing operational issues (Daigger & Boltz, 2011; De Vet, 2011). Regular maintenance, media cleaning, and performance optimization strategies can help maintain efficient treatment operations over time.

Biological Treatment Processes

C. Rotating Biological Contactors (RBCs)

Rotating Biological Contactors (RBCs) are a type of fixed-film biological treatment technology used for the treatment of wastewater. They consist of rotating discs or media that are partially submerged in the wastewater and support the growth of microbial biofilm. This chapter explores the configuration and components, operation and maintenance, as well as the advantages and limitations of RBCs. RBCs typically consist of multiple parallel shafts or discs mounted horizontally or vertically within a tank or channel (Waqas *et al.*, 2023). The discs are partially submerged in the wastewater, and as they rotate, they come into contact with the wastewater, allowing for the transfer of oxygen and nutrients to the microbial biofilm.

The rotating discs are the primary component of RBCs and provide a surface for the attachment and growth of microbial biofilm. They are typically made of plastic or other durable materials and are designed to withstand the mechanical stress of rotation. A drive mechanism, such as an electric motor or hydraulic system, rotates the discs at a controlled speed to ensure optimal contact between the biofilm and wastewater. RBCs are supported by a framework or structure that holds the rotating discs in place and provides stability during operation (Patwardhan, 2003; Tawfik *et al.*, 2006). Wastewater is evenly distributed over the rotating discs using a distribution system, such as spray nozzles or troughs, to ensure uniform contact between the wastewater and biofilm.

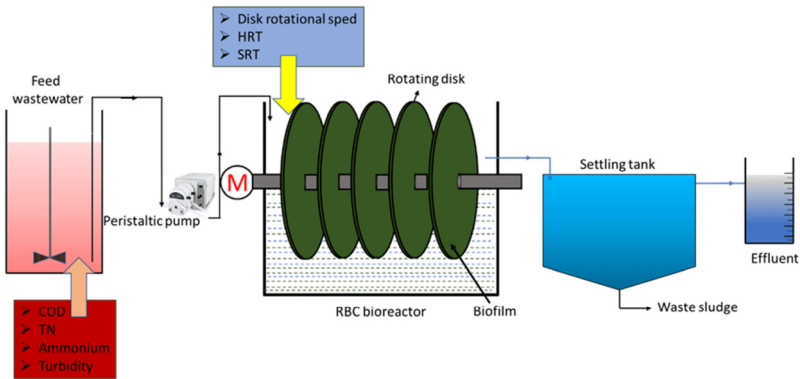


Figure 3. Rotating Biological Contactors (RBCs)

Wastewater enters the RBC tank or channel and comes into contact with the rotating discs, allowing for the transfer of oxygen and nutrients to the microbial biofilm. As the discs rotate, the biofilm degrades organic pollutants, removes nutrients, and stabilizes the wastewater. Excess biomass or sludge may accumulate on the surface of the rotating discs over time and require periodic removal to prevent clogging and maintain treatment efficiency (Abbasi, R. Sanjeevi, *et al.*, 2013; Hassard *et al.*, 2015). RBCs are equipped with control systems to monitor and regulate key operating parameters, such as rotational speed, hydraulic loading rate, and dissolved oxygen concentration, to optimize treatment performance. Routine inspection of RBC components, including rotating discs, drive mechanisms, and distribution systems, is essential to identify and address any mechanical issues or wear and tear. Periodic cleaning of the rotating discs and distribution system helps prevent fouling and biofilm buildup, ensuring consistent treatment performance. Lubrication of mechanical components, such as bearings and gears, is necessary to minimize friction and maintain the smooth operation of the RBC system.

RBCs provide effective treatment of wastewater due to the large surface area available for microbial biofilm growth and the efficient transfer of oxygen and nutrients. Compact Footprint: RBCs have a relatively small footprint compared to other biological treatment technologies, making them suitable for applications with limited space availability. RBCs require less energy compared to activated sludge systems or aerated lagoons, as they rely on passive aeration and mechanical rotation for treatment. RBCs may have limited capacity for nutrient removal, particularly nitrogen and phosphorus, compared to other treatment technologies. RBCs contain moving parts, such as rotating discs and drive mechanisms, which may require regular maintenance and replacement, increasing operational costs (Cortez *et al.*, 2008). RBCs may be sensitive to shock loads or fluctuations in wastewater flow and composition, which can affect treatment performance and stability.

Anaerobic Treatment Processes

Anaerobic digestion is a biological treatment process that converts organic matter into biogas (mainly methane and carbon dioxide) in the absence of oxygen. This chapter explores the process fundamentals, reactor types, and biogas production and utilization associated with anaerobic digestion. Anaerobic digestion is carried out by a consortium of microorganisms, including bacteria, archaea, and fungi, under oxygen-free conditions

(McCarty, 2001). These microorganisms break down complex organic compounds into simpler molecules through a series of biochemical reactions. Complex organic polymers such as proteins, carbohydrates, and lipids are hydrolyzed into soluble organic compounds by hydrolytic bacteria. Acidogenic bacteria ferment the soluble organic compounds into volatile fatty acids (VFAs), alcohols, and other intermediate products. Acetogenic bacteria further metabolize VFAs and other intermediates into acetic acid, hydrogen, and carbon dioxide. Methanogenic archaea convert acetate, hydrogen, and carbon dioxide into methane (CH₄) and carbon dioxide (CO₂) through a process known as methanogenesis. Factors Affecting Anaerobic Digestion: Key factors influencing anaerobic digestion include temperature, pH, organic loading rate, hydraulic retention time, and nutrient availability. Optimal operating conditions are essential to maintain microbial activity and maximize biogas production.

CSTRs are well-mixed reactors where wastewater is continuously fed into the reactor and effluent is continuously withdrawn. CSTRs are suitable for treating homogeneous feedstock and can achieve high levels of biogas production. ASBRs operate in batch mode, with sequential cycles of feeding, reaction, settling, and decanting. ASBRs offer flexibility in operation and are capable of treating variable feedstock and fluctuating organic loads (Kroeker et al., 1979). Fixed-film reactors utilize support media, such as granular sludge, biofilm carriers, or packed beds, to provide attachment surfaces for microbial growth. These reactors enhance biomass retention and are suitable for treating high-strength wastewater and complex organic compounds.

Biogas produced during anaerobic digestion consists primarily of methane (CH₄) and carbon dioxide (CO₂), with small amounts of trace gases such as hydrogen sulfide (H₂S), ammonia (NH₃), and water vapor. Biogas can be utilized as a renewable energy source for various applications. Biogas can be used to generate electricity and heat through cogeneration systems, providing on-site energy for wastewater treatment facilities and other operations. Direct Combustion: Biogas can be burned directly in boilers, furnaces, or gas engines to produce heat for space heating, water heating, or industrial processes. Biogas Upgrading: Biogas can be upgraded to biomethane, a purified form of methane, through processes such as pressure swing adsorption (PSA) or membrane separation. Biomethane can be injected into natural gas pipelines or used as a transportation fuel for vehicles (Ersahin et al., 2011). The solid and liquid residues remaining after anaerobic digestion, known as digestate, can be used as a soil amendment

or fertilizer in agriculture, providing valuable nutrients and organic matter to enhance soil health and fertility.

Anaerobic Treatment Processes

Anaerobic Membrane Bioreactors (AnMBRs)

Anaerobic Membrane Bioreactors (AnMBRs) represent an advanced form of anaerobic treatment technology that combines anaerobic digestion with membrane filtration for wastewater treatment. This chapter provides an overview of the technology, discusses its performance and applications, and addresses challenges and future perspectives. AnMBRs integrate anaerobic digestion with membrane filtration to separate treated effluent from biomass and suspended solids. Wastewater undergoes anaerobic digestion in the bioreactor, where organic pollutants are degraded by anaerobic microorganisms (Song *et al.*, 2018). The membrane filtration system, typically immersed or external, retains biomass and solids while allowing clean effluent to pass through.

AnMBRs utilize various membrane types, including hollow fiber membranes, flat sheet membranes, and tubular membranes, depending on the specific application and treatment objectives. Membranes are selected based on factors such as pore size, material composition, and membrane configuration to achieve efficient solids separation and permeate quality. AnMBRs can be configured in different layouts, such as submerged or external membrane configurations. Submerged AnMBRs immerse membrane modules directly into the bioreactor tank, while external AnMBRs employ separate membrane tanks or modules outside the bioreactor vessel (Skouteris *et al.*, 2012a). Each configuration offers unique advantages in terms of ease of operation, membrane cleaning, and process control.

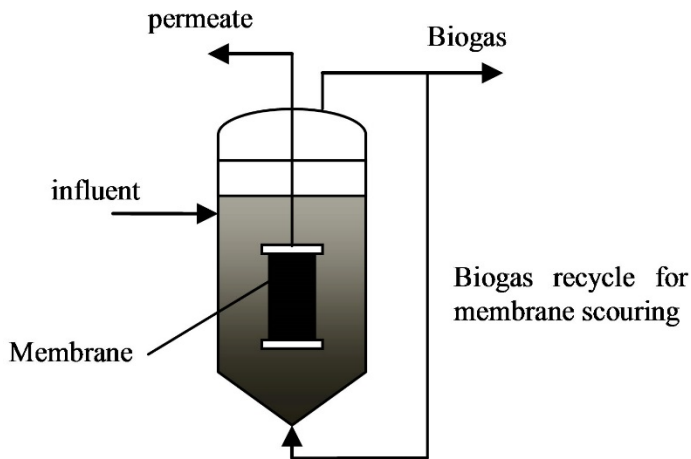


Figure 4. Anaerobic Membrane Bioreactors

Performance and Applications of Anaerobic Membrane Bioreactors

AnMBRs offer several advantages over conventional anaerobic digestion systems, including Enhanced Effluent Quality: Membrane filtration provides superior solids separation and effluent quality compared to conventional settling methods, resulting in treated effluent with low turbidity and suspended solids concentrations. AnMBRs require less space compared to conventional treatment systems, making them suitable for compact installations and retrofitting existing facilities with limited space availability (Ozgun *et al.*, 2013). Biogas produced during anaerobic digestion can be captured and utilized for energy generation, providing an additional source of renewable energy and reducing operational costs. AnMBRs are employed in various wastewater treatment applications, including used for treating municipal wastewater streams, particularly in decentralized or remote locations where space constraints and environmental considerations are critical. AnMBRs are applied in industrial sectors such as food and beverage, pulp and paper, and pharmaceuticals for treating high-strength organic wastewater and recovering valuable byproducts or resources (Ozgun *et al.*, 2013). AnMBRs facilitate the recovery of valuable resources from wastewater, including biogas for energy production, nutrients for fertilizer production, and purified water for reuse or discharge.

Membrane fouling remains a primary challenge in AnMBR operation, leading to reduced permeate flux, increased energy consumption, and membrane deterioration over time. Strategies for mitigating fouling include membrane cleaning, chemical pretreatment, and process optimization. Despite energy recovery from biogas, AnMBRs may still require significant energy input for membrane aeration, mixing, and pumping. Improving membrane efficiency, optimizing process parameters, and exploring alternative energy sources are essential for reducing overall energy consumption and enhancing sustainability. Future developments in AnMBR technology may focus on membrane materials, module design, and process optimization to improve performance, reliability, and cost-effectiveness (Liao *et al.*, 2006; Lin *et al.*, 2013). Emerging innovations such as membrane surface modification, hybrid membrane systems, and integrated process control strategies hold promise for overcoming current limitations and expanding the applicability of AnMBRs in wastewater treatment.

Advanced Biological Treatment Technologies

Membrane Bioreactors (MBRs)

Membrane Bioreactors (MBRs) represent a cutting-edge technology in biological wastewater treatment, combining biological processes with membrane filtration for superior effluent quality and process efficiency. This chapter delves into the configuration and operation of MBRs, highlights their advantages over conventional systems, and presents case studies showcasing their successful implementation. MBRs integrate biological treatment processes, such as activated sludge or biological nutrient removal, with membrane filtration to separate treated effluent from biomass and suspended solids (Stephenson *et al.*, 2000). Membrane modules, including hollow fiber, flat sheet, or tubular membranes, are submerged or installed externally within the bioreactor to provide solids separation and produce high-quality effluent. MBRs operate in continuous mode, with wastewater continuously fed into the bioreactor and treated effluent is continuously withdrawn through the membrane filtration system (Skouteris *et al.*, 2012b). Biomass retention within the bioreactor enhances treatment efficiency and enables extended solids retention times, resulting in enhanced nutrient removal and stable process performance.

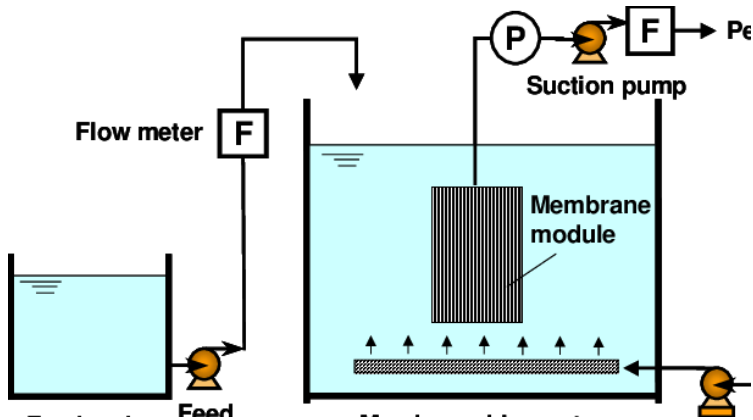


Figure 5. Membrane Bioreactors

Advantages over Conventional Systems of Membrane Bioreactors

MBRs produce effluent of exceptional quality, characterized by low turbidity, suspended solids, and pathogens, surpassing the standards achieved by conventional treatment processes. Membrane filtration effectively removes particulate matter, microorganisms, and contaminants, resulting in effluent suitable for reuse or environmentally sensitive discharge (Santos *et al.*, 2011). MBRs offer significant space savings compared to conventional treatment systems due to the elimination of secondary clarifiers and tertiary filtration units. Compact design and modular construction make MBRs suitable for decentralized applications, retrofitting existing facilities, and expanding treatment capacity within limited space constraints. MBRs enable process intensification by maximizing biomass concentration and treatment efficiency within a smaller footprint (Meng *et al.*, 2009). High biomass retention allows for higher organic loading rates, shorter hydraulic retention times, and increased nutrient removal, leading to enhanced treatment performance and reduced energy consumption.

Case Studies

The City of Singapore NEWater Plant: The Singapore NEWater Plant utilizes MBR technology to treat wastewater to ultra-pure standards for potable reuse. The plant produces high-quality reclaimed water that meets

stringent drinking water standards, contributing to Singapore's water sustainability goals and reducing reliance on imported water sources. Orange County Groundwater Replenishment System (GWRS), California, USA: The GWRS employs MBR technology to treat secondary effluent to advanced water purification standards for groundwater recharge. The system produces purified water that replenishes local aquifers, providing a reliable and sustainable water supply for Orange County residents and businesses. Thames Water Beckton Sewage Treatment Works, London, UK: The Beckton Sewage Treatment Works is one of the largest MBR facilities in the world, treating wastewater from the Greater London area. The MBR plant produces high-quality effluent suitable for discharge to sensitive receiving waters, protecting aquatic ecosystems and supporting biodiversity in the Thames estuary.

Advanced Biological Treatment Technologies

Sequencing Batch Reactors (SBRs)

Sequencing Batch Reactors (SBRs) represent a sophisticated approach to biological wastewater treatment, offering flexibility, efficiency, and superior treatment performance. This chapter explores the operating principle, design considerations, and applications and benefits of SBR technology. SBRs operate in batch mode, where wastewater treatment occurs in sequential cycles comprising several distinct phases, including filling, reaction, settling, decanting, and idle phases (Irvine & Busch, 1979). Each cycle follows a predetermined sequence controlled by an automated system or operator intervention.

Wastewater is introduced into the reactor vessel during the filling phase, filling it to a predetermined level. Biological treatment occurs during the reaction phase, where aeration and mixing promote the degradation of organic pollutants by aerobic microorganisms. Suspended solids settle to the bottom of the reactor during the settling phase, forming a sludge blanket. Treated effluent is withdrawn from the upper portion of the reactor during the decanting phase, leaving the settled sludge undisturbed. The reactor remains idle during the idle phase, allowing time for settling and decanting to complete before the next cycle begins. SBRs are equipped with advanced control systems that monitor and regulate key operating parameters, such as filling and decanting times, aeration rates, and dissolved oxygen levels (Irvine *et al.*, 1989). Process automation ensures optimal treatment performance and allows for adaptive control based on influent characteristics and treatment objectives.

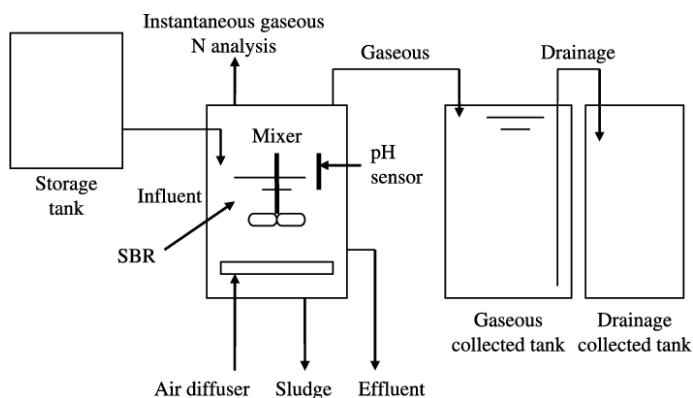


Figure 6. Sequencing Batch Reactors (SBRs)

Design Considerations

SBRs can be configured in various designs, including single-tank and multi-tank systems, depending on the treatment requirements and site-specific conditions. Single-tank SBRs offer simplicity and space savings, while multi-tank systems provide flexibility for sequential operation and process redundancy. Hydraulic design considerations include tank geometry, influent distribution, and mixing strategies to achieve uniform hydraulic conditions and prevent short-circuiting or dead zones within the reactor. Proper hydraulic design ensures efficient mixing, solids suspension, and biomass contact for effective treatment. SBR performance can be optimized through process parameter optimization, such as cycle time adjustment, aeration strategy optimization, and sludge wasting control (Al-Rekabi *et al.*, 2007). Monitoring and controlling key parameters enable operators to maximize treatment efficiency, nutrient removal, and sludge settling characteristics.

Applications and Benefits

SBRs are used in various wastewater treatment applications, including municipal wastewater treatment plants, industrial wastewater treatment, decentralized systems, and specialized treatment processes such as nutrient removal, bio-solids management, and water reuse. SBRs offer several advantages over conventional treatment systems, SBRs can achieve high levels of nitrogen and phosphorus removal through optimized process control and alternating anaerobic-anoxic-aerobic conditions. SBRs produce

less excess sludge compared to continuous flow systems, leading to lower disposal costs and reduced environmental impact. SBRs provide flexibility in operation and can adapt to fluctuations in wastewater flow and composition, making them suitable for treating variable or intermittent wastewater. SBRs offer energy-efficient operation through process optimization, aeration control, and variable cycle time scheduling (Mahvi, 2008). Reduced energy consumption and operational costs contribute to the sustainability of wastewater treatment operations.

Emerging Trends and Future Directions

Integration of Biological and Physicochemical Processes

The integration of biological and physicochemical processes represents a promising approach to enhancing the efficiency and resilience of wastewater treatment systems. This section explores the potential benefits, challenges, and applications of integrating biological and physicochemical treatment methods. Combining biological processes, such as activated sludge or anaerobic digestion, with physicochemical methods, such as membrane filtration or advanced oxidation, can synergistically improve pollutant removal and effluent quality. Integrated processes enable the recovery of valuable resources, such as nitrogen and phosphorus, from wastewater through chemical precipitation, ion exchange, or biological nutrient removal, contributing to resource conservation and sustainability (Tóth *et al.*, 2023). Integrated treatment systems offer flexibility in response to varying wastewater characteristics, allowing operators to optimize treatment performance, adapt to changing regulatory requirements, and address emerging contaminants or pollutants. Integrating biological and physicochemical processes requires careful design, operation, and control to ensure compatibility, minimize operational issues, and optimize treatment performance. Coordinating the operation of multiple treatment units and process streams within an integrated system presents challenges in terms of hydraulic balancing, solids management, and process synchronization (Ochando-Pulido *et al.*, 2017). Implementing integrated treatment systems may entail higher capital and operational costs compared to individual treatment methods, requiring careful cost-benefit analysis and consideration of long-term sustainability.

Integrated biological-chemical processes, such as enhanced biological phosphorus removal (EBPR) coupled with chemical precipitation or biological nitrogen removal combined with membrane filtration, are applied

for efficient nutrient removal in wastewater treatment plants. Advanced oxidation processes (AOPs), such as ozonation or UV/H₂O₂ treatment, integrated with biological treatment units, are utilized for the removal of emerging contaminants, pharmaceuticals, and micropollutants from wastewater (Mohapatra *et al.*, 2010). Integrated treatment systems incorporating biological treatment, membrane filtration, and advanced disinfection technologies enable the production of high-quality reclaimed water for non-potable reuse applications, such as irrigation, industrial processes, and environmental restoration.

Resource recovery from wastewater presents an opportunity to transform wastewater treatment facilities into resource recovery hubs, where valuable resources such as energy, nutrients, and water are reclaimed and reused. This section explores emerging trends, technologies, and challenges in resource recovery from wastewater. Anaerobic digestion of organic matter in wastewater produces biogas, primarily methane, which can be captured and utilized for energy generation through combined heat and power (CHP) systems or upgraded to biomethane for injection into natural gas pipelines or use as a transportation fuel (Kumar *et al.*, 2021). Microbial fuel cells harness the electrochemical activity of microorganisms to generate electricity from organic matter in wastewater, offering a sustainable and decentralized energy recovery solution for off-grid applications or remote locations.

Recovery of phosphorus as struvite (magnesium ammonium phosphate) through chemical precipitation from wastewater side streams or anaerobically digested sludge offers a valuable nutrient source for fertilizer production, reducing reliance on finite phosphate reserves. Biological processes such as anaerobic digestion, biological phosphorus removal, and nitrogen removal via nitrification-denitrification enable the recovery of nitrogen and phosphorus from wastewater, supporting nutrient cycling and circular economy principles. Advanced membrane filtration technologies, including reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF), enable the production of high-quality reclaimed water suitable for potable and non-potable reuse applications, including irrigation, industrial processes, and groundwater recharge (Ioannou *et al.*, 2015). Advanced treatment processes such as ozonation, UV disinfection, and activated carbon adsorption are employed to remove trace contaminants, pathogens, and disinfection byproducts from reclaimed water, ensuring compliance with stringent water quality standards and public health protection.

Application of Artificial Intelligence in Process Control

The application of artificial intelligence (AI) in wastewater treatment process control represents a transformative trend that offers opportunities to enhance efficiency, optimize performance, and reduce operational costs. This section explores the integration of AI technologies, including machine learning, predictive analytics, and control algorithms, in wastewater treatment operations. Machine learning algorithms, including neural networks, support vector machines, and random forests, are trained on historical process data to develop predictive models for wastewater treatment performance, enabling real-time monitoring, fault detection, and process optimization (Sathvara *et al.*, 2023; Wen & Vassiliadis, 1998). AI-based predictive models analyze large datasets of process variables, influent characteristics, and environmental conditions to identify patterns, correlations, and trends, facilitating proactive decision-making, adaptive control strategies, and predictive maintenance.

Model predictive control utilizes dynamic process models and optimization algorithms to predict future system behavior and compute optimal control actions, such as setpoint adjustments, flow rate changes, and chemical dosing rates, to achieve desired treatment objectives while minimizing energy consumption and operating costs. AI-based control systems integrate feedback loops, sensor data, and actuation mechanisms to continuously monitor and adjust process parameters in response to changing conditions, disturbances, or variations in influent characteristics, ensuring stable operation and consistent effluent quality. AI-enabled remote sensing technologies, including satellite imaging, drones, and IoT sensors, provide real-time monitoring of water quality parameters, environmental conditions, and infrastructure assets, enabling early detection of pollution events, leaks, or system failures and facilitating timely intervention and response (Ankitkumar B Rathod *et al.*, 2022; R Kshirsagar *et al.*, 2022). AI-driven autonomous operation and control systems automate routine tasks, optimize resource allocation, and streamline decision-making processes, reducing operator workload, human error, and manual intervention while improving system reliability, resilience, and adaptability.

Sustainability and circular economy principles are driving forces shaping the future of wastewater treatment, emphasizing resource recovery, energy efficiency, and environmental stewardship. This section explores strategies, initiatives, and emerging trends in sustainable wastewater management and circular economy practices. Promoting water reuse and recycling initiatives, including dual plumbing systems, gray water reuse, and decentralized

treatment facilities, reduces freshwater consumption, minimizes wastewater discharge, and enhances water security in water-stressed regions. Implementing integrated resource recovery strategies, such as energy generation from biogas, nutrient recovery from wastewater, and production of value-added products from wastewater byproducts, supports circular economy principles and reduces reliance on finite resources. Harnessing renewable energy sources, such as solar photovoltaic, wind turbines, and hydropower, to power wastewater treatment facilities reduces greenhouse gas emissions, enhances energy resilience, and contributes to climate change mitigation efforts (Ankitkumar B Rathod *et al.*, 2023; Li *et al.*, 2021). Implementing energy management systems, including energy audits, demand-side management, and energy-efficient technologies, optimizes energy consumption, reduces operational costs, and improves overall energy performance in wastewater treatment operations.

Designing closed-loop systems that minimize resource inputs, maximize resource recovery, and eliminate waste streams through process optimization, material reuse, and product recycling, promotes circularity, resource efficiency, and environmental sustainability in wastewater treatment (Kamali *et al.*, 2021; Prashantkumar B. Sathvara *et al.*, 2023). Fostering partnerships and collaboration among industries, municipalities, and stakeholders to exchange resources, byproducts, and expertise, creates synergies, reduces environmental impact, and enhances economic viability through shared infrastructure, resource utilization, and waste valorization initiatives.

Policy and Regulatory Frameworks in Wastewater Treatment

Aligning wastewater management practices with the United Nations Sustainable Development Goals (SDGs), including Goal 6 (Clean Water and Sanitation), Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 12 (Responsible Consumption and Production), guides policy development, investment decisions, and stakeholder engagement in advancing sustainable wastewater solutions (Dilekli & Cazcarro, 2019). Adhering to stringent environmental regulations, effluent quality standards, and pollution prevention measures, ensures regulatory compliance, protects public health, and mitigates environmental risks associated with wastewater discharge, contamination, and pollution.

Engaging stakeholders, including policymakers, industry leaders, community members, and the public, through outreach programs, educational campaigns, and participatory decision-making processes, fosters awareness, promotes behavior change, and builds support for sustainable wastewater management initiatives. Facilitating knowledge sharing, capacity building, and best practices dissemination among water professionals, researchers, academia, and civil society organizations, strengthens institutional capacity, fosters innovation, and accelerates the adoption of sustainable wastewater solutions globally (Hendry *et al.*, 2017). Investing in research, innovation, and technology development in areas such as advanced treatment processes, smart monitoring and control systems, and decentralized wastewater solutions, fosters scientific discovery, technological breakthroughs, and transformative solutions to address complex water challenges. Promoting public-private partnerships, joint ventures, and collaborative initiatives between government agencies, private sector entities, academia, and non-profit organizations, catalyzes innovation, accelerates technology adoption, and drives sustainable development outcomes in wastewater management.

Different Applications of Wastewater Treatment Plants

A. Industrial Wastewater Treatment

Industrial wastewater treatment presents unique challenges and opportunities due to the diverse composition and complexity of industrial effluents. This section examines case studies showcasing innovative approaches and best practices in industrial wastewater treatment.

Chemical Manufacturing, Food and Beverage Plant Processing Facility

A chemical manufacturing plant faced compliance issues with effluent discharge limits for heavy metals and organic pollutants, posing environmental risks and regulatory concerns. The plant implemented a multi-stage treatment system incorporating physical-chemical treatment, biological oxidation, and advanced filtration technologies to remove contaminants and meet effluent quality requirements. The integrated treatment system achieved significant reductions in heavy metal concentrations and organic pollutant levels, ensuring compliance with regulatory standards and minimizing environmental impact. By reclaiming treated wastewater for process reuse and recycling, the plant reduced