International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Conventional and Advanced Wastewater Treatment Techniques; Development of Sustainable Environment and Production of Biofertilizers

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DOI: https://doi.org/10.55248/gengpi.5.0124.0364

ABSTRACT

Wastewater treatment is currently a vital and expanding area in water purification. Numerous reasons, including urbanization, industry, agricultural farming, livestock, oil spills, deforestation, global warming, radioactive waste, and population growth, are mostly to blame for the release of various contaminants into water supplies. Many conventional methods of treating wastewater were previously introduced, including thermal treatment, ion exchange, adsorption, electrochemical degradation, coagulation, and chemical precipitation. The aforementioned methods are ineffective for cleaning water due to several disadvantages, including high energy requirements, the creation of unwanted by-products, harmful consequences, financial concerns, etc. This review article seeks to offer a thorough examination of the development of a sustainable environment and the production of Biofertilizers by adopting advanced wastewater treatment techniques in which filtration of water by using (nanotechnology) nanofibrous membrane (NF), Enhanced biological phosphorus removal (EBPR), Microbial fuel cells (MFCs) and advanced oxidation are included. Activated sludge produced during wastewater treatment can be used to make biofertilizers. This review highlights the advance treatment techniques for the sustainability and eco-friendly environment and to minimize the impact of water pollution on humans, animals as well as environment.

Keywords: Wastewater treatment, sustainable development goals, nanotechnology, microbial fuel cells oxidation, biofertilizers

1. Introduction

Wastewater treatment is essential to maintaining environmental sustainability, safeguarding public health, and ensuring the sustainable use of water resources. Numerous harmful contaminants, such as bacteria, viruses, pathogens, and chemical pollutants, can be found in untreated wastewater (Akpor and Muchie 2011). Waterborne diseases like diarrhoea, cholera, typhoid, hepatitis, amebiasis, gastroenteritis, campylobacteriosis, giardiasis, scabies, and worm infections can spread when untreated wastewater is discharged into water bodies or used for irrigation, posing a serious risk to public health (Pedley and Howard 1997). Wastewater treatment procedures eliminate or lessen these impurities, ensuring the water is suitable for a range of applications, such as irrigation of agricultural fields, recreational pursuits, and drinking (Bouwer 2000). Wastewater discharges into natural water bodies can have detrimental effects on aquatic ecosystems. High levels of nutrients, such as nitrogen and phosphorus, in untreated wastewater, can lead to eutrophication, causing oxygen depletion and harming aquatic life (Bhat and Qayoom 2021). Additionally, toxic substances present in wastewater can bio-accumulate in the food chain, negatively impacting the health and biodiversity of aquatic organisms. Different types of parasite in the wastewater cause serious health issues. Proper wastewater treatment minimizes these ecological risks, preserving the balance and integrity of ecosystems (Arthington, Naiman et al. 2010). Freshwater resources are finite, and the increasing water demand necessitates the responsible management of available supplies. Wastewater treatment enables the recycling and reuse of treated water for non-potable purposes like irrigation, industrial processes, and groundwater recharge (Wintgens, Melin et al. 2005). By implementing water reuse strategies, wastewater treatment contributes to water conservation, reduces the strain on freshwater sources, and ensures a sustainable water supply for various sectors (Al-Zubari, Al-Turbak et al. 2017). The introduction of numerous traditional wastewater treatment techniques, such as thermal treatment, ion exchange, adsorption, electrochemical degradation, coagulation, and chemical precipitation, occurred in the past (Saravanan et al. 2021). The previously mentioned techniques don't work well for purifying water because of a variety of drawbacks, such as high energy needs, the production of undesirable by-products, negative outcomes, cost issues, etc. The advancement of sustainable environments and biofertilizer production through the use of cutting-edge wastewater treatment techniques, which include advanced oxidation and nanofibrous membrane water filtration. Biofertilizers can be created from activated sludge, which is produced during wastewater treatment (Rani et al. 2023). Wastewater treatment is essential for protecting public health, preserving ecosystems, ensuring water resource sustainability, mitigating pollution, and supporting sustainable development (Connor 2015). The treatment of wastewater is essential to the achievement of various sustainable development goals (SDGs). First of all, it makes a substantial contribution to the availability of safe water resources by guaranteeing clean water and sanitation (SDG 6) (Obaideen et al. 2022). Additionally, it directly contributes to SDG 3's focus on health and well-being by stopping the spread of waterborne illnesses through appropriate treatment methods. Fostering industry, innovation, and infrastructure is in line with integrating sustainable and innovative technology in wastewater treatment (SDG 9) (Awan et al. 2021).

Furthermore, it facilitates conscientious consumption and production (SDG 12) by encouraging water efficiency and mitigating environmental impacts. The conservation of terrestrial and aquatic ecosystems against pollution is linked to both Life on Land (SDG 15) and Life below Water (SDG 14). Through the adoption of energy-efficient procedures and the mitigation of greenhouse gas emissions, wastewater treatment also supports climate action (SDG 13) (Delanka-Pedige et al. 2021). Last but not least, reaching these objectives requires collaboration to achieve the goals (SDG 17), highlighting the significance of joint efforts between communities, businesses, and governments in sustainable wastewater management. Wastewater treatment processes encounter multifaceted challenges. The composition of wastewater is very different, containing a variety of contaminants, from chemicals to pathogens, which complicates treatment processes (Akpor et al. 2014). These processes need high resource requirements which include significant amounts of energy and materials raise operational expenses and environmental issues. Because emerging contaminants are constantly changing, it can be challenging to identify and remove them, including pharmaceuticals. The efficiency of treatment processes is further impacted by climate change, which also introduces variability in wastewater characteristics and volume. A crucial but difficult part of wastewater management is educating the public about proper waste disposal and promoting sustainable practices (Leitão et al. 2006).

Conventional Wastewater Treatment Techniques

Conventional wastewater treatment technologies form the backbone of municipal and industrial wastewater treatment systems (Bera, Godhaniya et al. 2022). These processes are designed to remove a significant portion of pollutants and contaminants from wastewater before its discharge into the environment

1. Primary Treatment

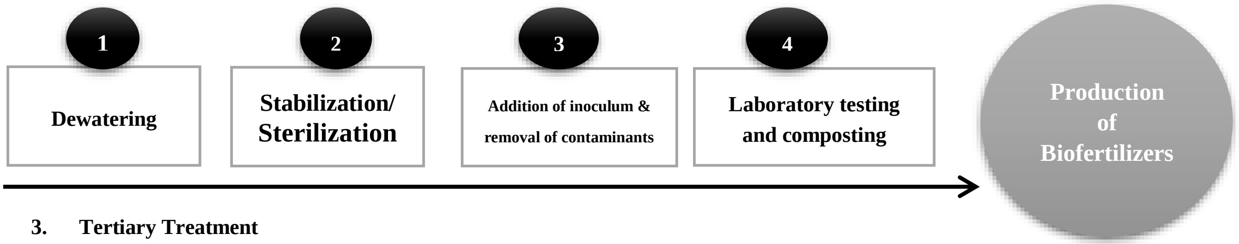
Primary treatment is the initial step in wastewater treatment, primarily aimed at removing large solids and floating debris (Awaleh and Soubaneh 2014). The main processes involved in primary treatment include screening and grit removal. Wastewater passes through screens to remove large objects like sticks, plastics, and rags (Markin, Lepikhin et al. 2020). Grit chambers or sedimentation tanks are used to settle heavy inorganic particles, such as sand and gravel, which may damage downstream equipment (Jasim 2020).

2. Secondary Treatment

Secondary treatment processes focus on the removal of organic matter and suspended solids from wastewater (Sonune and Ghate 2004). These processes rely on the activities of microorganisms to break down organic contaminants. Common secondary treatment methods include activated sludge process and trickling filters Wastewater is mixed with a microbial culture (activated sludge) in aeration tanks, facilitating the biological degradation of organic pollutants (Fang, Cai et al. 2013).

Wastewater is distributed over a bed of rocks or plastic media coated with microbial biofilm, where organic matter is biologically oxidized (Malakar, Saha et al. 2017).

Activated sludge, a by-product of secondary wastewater treatment, is converted into a valuable resource for agriculture through a series of carefully planned steps in the production of bio-fertilizer (Engida et al. 2020). The secondary treatment is followed by dewatering procedures to lower the moisture content of the activated sludge. After that, stabilization methods like aerobic or anaerobic digestion are used to get rid of pathogens and reduce the amount of organic matter (Seruga et al. 2020). After stabilized, the sludge can be composted to improve its nutrient profile and guarantee that any possible contaminants are removed. The composition of the bio-fertilizer may be optimized by adding more organic or mineral additives (Chojnacka et al. 2020). Strict quality control procedures are carried out to fulfil legal requirements, guaranteeing the finished product's effectiveness and safety. After the production on biofertilizers, these fertilizers are tested on different plants to check the growth rate and production.

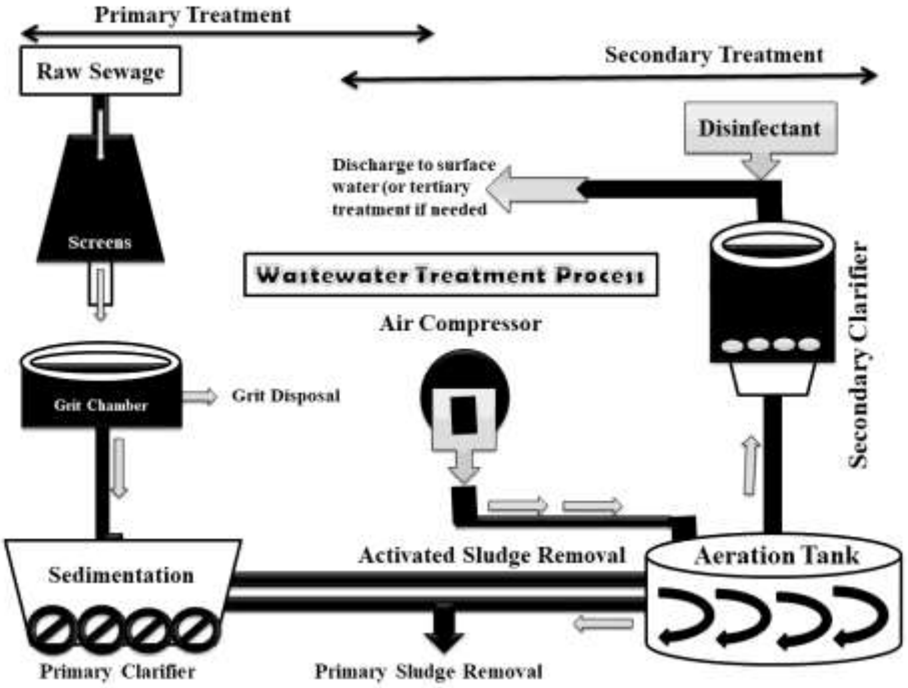


3. Tertiary Treatment

Tertiary treatment is a subsequent stage to further enhance the quality of treated wastewater, particularly for specific purposes like water reuse or discharge into sensitive environments (Pintilie, Torres et al. 2016). Tertiary treatment methods include filtration, disinfection, and nutrients removal by eliminating excess nutrients such as nitrogen and phosphorus. Techniques such as sand filters, multimedia filters, or membrane filtration (microfiltration, ultrafiltration) are employed to remove remaining suspended solids and fine particles (Bairagi and Ali 2020). Chemical disinfection (chlorination, ozonation) or physical disinfection (UV irradiation) is applied to eliminate pathogens and unwanted nutrients and ensure the microbial safety of treated wastewater (Shi, Chen et al. 2021). Tertiary treatment is mostly used for the purification of water to make it drinkable by using different techniques.

Advanced Wastewater Treatment Technologies

Advanced wastewater treatment technologies go beyond the conventional treatment processes to achieve a higher degree of pollutant removal, particularly for challenging contaminants or specific water reuse applications (Ruel, Choubert et al. 2011). These technologies utilize innovative and advanced processes to enhance the efficiency of wastewater treatment and improve the quality of treated effluent.



1. **Membrane Bioreactors (MBRs)**

Membrane bioreactors integrate membrane filtration technologies with biological treatment. It involve the use of semi-permeable membranes to separate suspended solids, dissolved pollutants, and microorganisms from wastewater (Gupta, Ali et al. 2012). Membrane filtration processes used in advanced treatment include Microfiltration (MF), Ultrafiltration (UF), Nanofibrous membrane filtration and Reverse Osmosis (RO). In microfiltration membranes with larger pore sizes to remove suspended solids, bacteria, and some protozoa (Branch, Trinh et al. 2021). Ultrafiltration membranes with smaller pore sizes to remove fine suspended solids, colloids, viruses, and larger organic molecules (Warsinger, Chakraborty et al. 2018). A nano-fibrous membrane filtration system is an advanced technology that utilizes membranes composed of nanofibers for the filtration of water or other liquids in wastewater treatment processes (Shafqat, Rehman et al. 2022). Nano-fibrous membranes are characterized by extremely small fibre diameters in the nanometer range, typically below 100 nanometers. Nanofiltration removes divalent ions, organic compounds, and certain small molecules, providing a partial softening effect. (Adusei-Gyamfi, Ouddane et al. 2019). Reverse osmosis utilizes highly selective membranes to remove dissolved solids, salts, and organic compounds, producing high-quality water suitable for various reuse applications (Holloway, Regnery et al. 2014).

2. **Advanced Oxidation Processes (AOPs)**

Advanced oxidation processes involve the generation of highly reactive hydroxyl radicals ($\cdot OH$) to oxidize and degrade recalcitrant organic compounds in wastewater (Deng and Zhao 2015). Common AOPs used in advanced treatment include Ozone oxidation, UV Irradiation, and Fenton Reaction. Ozone oxidation is introduced into wastewater to oxidize organic contaminants, eliminate color, and destroy pathogens (Rice 1996). Ultraviolet (UV) light is used to generate OH^- radicals in the presence of oxidizing agents or catalysts, enhancing the oxidation of organic pollutants (Ghanbari and Moradi 2017). Fenton reaction involves the addition of ferrous iron (Fe^{2+}) and hydrogen peroxide (H_2O_2) to generate OH^- radicals, effectively breaking down organic contaminants (Koprivanac and Kusic 2007).

3. **Microbial Fuel Cells (MFCs)**

Microbial fuel cells a source of renewable energy generation, an operating device that convert chemical energy into electricity by using bacterial metabolic machinery, consisting of a cathode and anode (Srivastava et al. 2022). A salt bridge also called proton exchange membrane which separates cathode chamber from anode chamber. MFC has been primarily centred for the treatment of domestic, industrial, agricultural and municipal water waste by generating electricity and hydrogen (Saravanan et al. 2022). Researchers and scientists are working for the construction of different microbial fuel cells in which single chamber microbial fuel cells (SCMFCs), double chamber microbial fuel cells (DCMFCs) are included.

4. Enhanced Biological Phosphorus Removal (EBPR)

An innovative wastewater treatment method called Enhanced Biological Phosphorus Removal (EBPR) is intended to remove phosphorus from wastewater in a selective manner, thereby reducing environmental concerns associated with nutrient pollution. EBPR begins with an anaerobic phase where polyphosphate-accumulating organisms PAOs absorb and store phosphorus in the form of polyphosphate granules (Warsinger, Chakraborty et al. 2018). This process is based on the idea of utilizing particular microbial communities, particularly polyphosphate-accumulating organisms (PAOs). Enzymes that transform organic phosphorus compounds into soluble forms are released when an aerobic phase is subsequently exposed to the mixture. Most importantly, the PAOs absorb and hold onto the released phosphorus in their biomass during this phase. After settling, the enriched biomass is separated from the treated water, which is now phosphorus-depleted. The efficiency of EBPR resides in its ability to remove phosphorus without the need for chemical additives, providing wastewater treatment facilities especially those subject to strict phosphorus discharge regulations with an environmentally friendly method (Koprivanac and Kusic 2007). Nonetheless, optimizing performance and overcoming potential operational challenges require precise control of microbial populations and environmental conditions.

5. Constructed Wetlands and Natural Treatment Systems

Constructed wetlands mimic natural wetland ecosystems and utilize vegetation, soil, and microbial processes to treat wastewater (Gopal 1999). These systems provide effective treatment while promoting biodiversity and ecological benefits. Types of constructed wetlands and natural treatment systems are free water surface (FWS) wetlands, subsurface flow (SSF) wetlands and hybrid systems. Free water surface wetlands have wastewater flows through shallow surface water, allowing the growth of wetland plants and microbial activity to remove contaminants (Zhang, Zheng et al. 2010). Subsurface Flow (SSF) Wetlands have wastewater percolates through a bed of gravel or soil planted with wetland vegetation, facilitating treatment through biological, physical, and chemical processes (Vymazal 2011). Hybrid Systems are combination of constructed wetlands with other treatment technologies, such as activated sludge or filtration, to enhance pollutant removal (Liu, Zhao et al. 2015).

Energy Efficiency and Resource Recovery in Wastewater Treatment

Energy efficiency and resource recovery are essential aspects of sustainable wastewater treatment systems (Akyol, Foglia et al. 2020). The optimization of energy use and the extraction of valuable resources from wastewater not only contribute to cost savings but also enhance the overall environmental performance of the treatment process

1. Anaerobic Digestion for Biogas Production

Anaerobic digestion is a widely adopted process that treats organic waste in wastewater, such as sludge or high-strength organic effluents, in the absence of oxygen (Rajeshwari, Balakrishnan et al. 2000). The process produces biogas, primarily composed of methane (CH_4), which can be utilized as a renewable energy source. Anaerobic digester configurations and operation, Biogas utilization for electricity generation or direct use as a heating fuel and Co-digestion of wastewater sludge with other organic waste streams for enhanced biogas production Wastewater contains valuable nutrients, such as phosphorus (P) and nitrogen (N), which can be recovered and reused as fertilizers or for other applications (Cai, Park et al. 2013). Nutrient recovery reduces the reliance on finite mineral resources and minimizes the environmental impact associated with the production and use of synthetic fertilizers (Sniatala, Kurniawan et al. 2023). Phosphorus recovery technologies, such as struvite precipitation and thermal hydrolysis Nitrogen recovery methods, such as biological or chemical processes for ammonium removal and conversion. Bioelectrochemical systems (BES) integrate microbial processes with electrochemical reactions to generate electricity or valuable chemicals from wastewater (Schröder, Harnisch et al. 2015). BES technologies, such as microbial fuel cells and microbial electrolysis cells, offer opportunities for energy production and resource recovery (Foley, Rozendal et al. 2010). Key points covered in this include: Working principles and configurations of bio electrochemical systems, Electricity generation from organic matter degradation and electrochemical production of chemicals, such as hydrogen gas or value-added compounds.

2. Energy Optimization and Efficiency Measures

Energy optimization strategies and technologies employed in wastewater treatment plants to reduce energy consumption and improve overall efficiency (Longo, d'Antoni et al. 2016). Process optimization and control to minimize energy demands Integration of energy-efficient equipment and technologies, such as high-efficiency pumps and blowers, utilization of renewable energy sources, such as solar or wind power, to offset energy requirements and energy recovery from wastewater treatment processes, such as heat recovery from anaerobic digestion or biogas utilization (Denkena et al. 2020). The integration of energy efficiency measures and resource recovery strategies in wastewater treatment systems not only contribute to cost savings but also promote environmental sustainability. By generating renewable energy, recovering valuable resources, and minimizing energy consumption, wastewater treatment plants can become more self-sufficient, reduce their carbon footprint, and support the transition towards a circular economy approach (Ghimire et al 2021).

3. Decentralized Wastewater Treatment Systems

Decentralized wastewater treatment systems compromise an alternative method to centralized treatment plants by treating wastewater (Wilderer and Schreff 2000). These systems provide many advantages, including lower infrastructure costs, reduced energy requirements, and increased flexibility in wastewater management. A decentralized wastewater treatment system discovers the benefits, challenges, and various technologies associated with decentralized approaches. Decentralized systems can be more economical, especially in areas with low population density or remote locations where the installation of extensive sewer networks and centralized treatment plants is not feasible (Naik and Stenstrom 2016). Decentralized systems eliminate the need for large-scale conveyance networks, minimizing the demand for extensive pipelines and pumping stations (Misconel, Zöphel et al. 2021). Decentralized systems can be designed and scaled according to specific site requirements, allowing for modular expansion and adaptation to changing needs. Decentralized systems offer opportunities for localized resource recovery, such as energy generation from anaerobic digestion or nutrient reuse in agriculture (Capodaglio 2017).

Type of Treatment System	Characteristics	Reference
Packaged Plants	Packaged Plants are pre-fabricated treatment units are compact and designed for easy installation, typically consisting of multiple treatment stages in a single container or module	(Najan, Rathod et al. 2021)
Sequencing Batch Reactors (SBR):	Sequencing Batch Reactors (SBR): SBRs treat wastewater in batches, allowing for biological treatment, settling, and decanting within a single tank	(Fontenot, Bonvillain et al. 2007)
Constructed Wetlands Systems	Constructed Wetlands systems utilize natural processes involving wetland vegetation, soil, and microbes to treat wastewater, providing ecological benefits and aesthetic value.	(ElZein, Abdou et al. 2016)
Septic Systems	Septic Systems are commonly used in rural areas, septic systems treat wastewater through a combination of settling, microbial digestion, and soil infiltration	(Adegoke and Stenstrom 2019)

Table 1. Types of Decentralized Wastewater Treatment Systems

Environmental Impacts and Sustainability in Wastewater Treatment

Wastewater treatment processes have the potential to impact the environment, and ensuring their sustainability is crucial for long-term environmental protection (Priyadharshini, Babu et al. 2021). Environmental impacts and sustainability explores the potential effects of wastewater treatment on the environment and discusses strategies to minimize these impacts. Treated wastewater effluents can still contain residual pollutants that may have adverse effects on aquatic ecosystems (Ebele, Abdallah et al. 2017). This subsection focuses on the potential ecotoxicity of treated effluents and the importance of monitoring and controlling the discharge of contaminants, such as heavy metals, organic compounds, and emerging pollutants. Strategies to mitigate ecotoxicity include advanced treatment processes, such as activated carbon filtration or ozonation, to remove or degrade persistent pollutants (Völker, Stapf et al. 2019).

Wastewater treatment plants utilize significant amounts of energy consumption for various processes, including aeration, sludge treatment and pumping (Gurung, Tang et al. 2018). The environmental impact of energy consumption and highlights the importance of energy efficiency measures to reduce greenhouse gas emissions (Huo, Wang et al. 2009). Implementing energy optimization strategies, consuming renewable energy sources, and discovering energy recovery from wastewater treatment processes can contribute to a more sustainable operation. The reuse of treated wastewater for non-potable purposes, such as irrigation or industrial processes, is an effective approach for water conservation (Beekman 1998). The benefits of water reuse and addresses potential concerns regarding the quality and safety of reclaimed water (Miller 2006). It highlights the importance of implementing robust treatment processes, monitoring, and risk assessment to ensure that reused water meets quality standards and does not pose health or environmental risks. Life cycle assessment (LCA) is a appreciated tool for estimating the environmental impacts of wastewater treatment systems widely (Corominas, Byrne et al. 2020). The importance of conducting LCAs to assess the sustainability of different treatment and technologies, considering factors such as energy consumption and emissions, resource use and environmental impacts (Vieira, Calmon et al. 2016). LCA can inform decision-making processes and monitor the selection of the most sustainable treatment options.

Emerging Technologies in Wastewater Treatment

The emerging technologies discover the latest advancements and possible developments in wastewater treatment. It discusses emerging technologies and processes, research trends, and future perspectives that have the potential to transform the field. Sensor technologies, such as remote sensing real-time monitoring devices, advanced analytical tools and remote sensing are developing wastewater treatment by providing accurate and timely data on process parameters, water quality, and system performance (Chang, Imen et al. 2015). The role of sensor technology in optimizing treatment processes, facilitating automation, and enabling proactive decision-making for process control, grip and maintenance. Artificial intelligence (AI) and machine learning (ML) techniques are progressively being applied in wastewater treatment to increase process optimization, system performance and predictive modelling (Bagherzadeh, Mehrani et al. 2021). The potential of AI and ML algorithms in data analysis, pattern recognition & modification, and process optimization, leading to more efficient and adaptive wastewater treatment systems. The development of novel materials and technologies offers new possibilities for enhancing treatment efficiencies and addressing emerging challenges (Moore and Shi 2014). This highlights advances in areas such as membrane materials, catalysts, nanotechnology, and adsorbents, which can improve pollutant removal, increase energy efficiency, and enhance resource recovery in wastewater treatment processes.

International standards and guidelines

Policy and regulatory frameworks play a vital role in guiding, maintaining and governing wastewater treatment practices (Breitenmoser, Quesada et al. 2022). They provide a regulatory framework for environmental protection, sustainability, public health, and clean water management. The policy and regulatory frameworks discovers the importance of international standards, policies, guidelines, and economic incentives in shaping wastewater treatment techniques. International organizations, such as the World Health Organization (WHO) and the United Nations Environmental Program (UNEP), have developed some standards, protocols and guidelines that set benchmarks for wastewater treatment and discharge (Organization 2006). These standards cover several characteristics, including water quality, nutrients availability, effluent limits, and treatment technologies (Nasir, Fatma et al. 2022). The importance of international standards in confirming consistent and sustainable wastewater treatment techniques worldwide (Kanwal, Sajjad et al. 2020). Governments establish regulations, protocols and guidelines at national, regional, and local levels to confirm compliance with environmental and public health standards (Gostin, Monahan et al. 2019). These regulations define effluent quality standards, nutrients availability in water, discharge permits, monitoring requirements, and compliance obligations for wastewater treatment facilities.

Research and Innovation Policies

Governments and funding organizations play a critical part in supporting research and advancement in wastewater treatment (Parker 2011). The importance of research funding, collaboration between academia, organization and industry, and the development of research, innovative and advanced strategies. Research policies promote the advancement of technologies, processes, and the best practices in wastewater treatment, addressing emerging challenges and contributing to sustainable water management (Qu, Dai et al. 2022). Robust policy and regulatory frameworks are essential for driving sustainable wastewater treatment practices, ensuring compliance, and protecting the environment and public health (Thakur 2021). Effective implementation and enforcement of regulations, periodic review of standards, and stakeholder engagement are crucial for the success of these frameworks (Bourne 2016). Additionally, international collaboration and knowledge-sharing platforms contribute to the harmonization of policies and the dissemination of best practices globally, facilitating the development of sustainable wastewater treatment systems worldwide.

Challenges in Wastewater Treatment

The field of wastewater treatment faces numerous challenges that require ongoing research, advancement and innovation to address effectively (Sharma, Vanapalli et al. 2020). The challenges and future research directions highlights significant areas where further investigation is needed to improve wastewater treatment processes, technologies and overcome existing limitations. Emerging contaminants, such as pharmaceuticals, personal care products, micro-plastics, heavy metals , pesticides, herbicides , polychlorinated biphenyls (PCBs), dioxins , nano particles, radioactive compounds and endocrine-disrupting compounds, pose significant challenges for wastewater treatment (Necibi, Dhiba et al. 2021). Future research should focus on developing new treatment technologies and processes capable of effectively removing these contaminants. In the advanced treatments improvement in the efficiency and cost-effectiveness of wastewater treatment processes should be included. Future research should explore innovative approaches and technologies to optimize treatment efficiency, minimize the production of unwanted by-products, reduce energy consumption, and minimize the use of chemicals while maintaining high treatment performance. This includes discovering process intensification techniques, innovative reactor designs, and the integration of emerging technologies to improve overall system efficiency (Nasir, Bibi et al.). Effective translation of research findings into practical applications is essential to realize the potential of new technologies and treatment methodologies (Rubio, Schoenbaum et al. 2010). Future research should attention on connecting between research and implementation by directing pilot-scale studies, assessing their feasibility in real-world scenarios, demonstrating the scalability of innovative technologies and developing guidelines for their successful deployment in wastewater treatment facilities. The recovery of resources from wastewater, such as energy, nutrients, and water, is an area of increasing interest (Van Lier 2008). Future research should discover ways to improve the economic viability of resource extraction technologies, improve resource recovery processes and develop innovative approaches for utilizing the by-products of wastewater treatment in various regions. This includes exploring the potential of emerging technologies, such as electrochemical processes and microbial fuel cells (MFCs), for efficient and sustainable resource recovery (Chin, Phuang et al. 2022).

Conclusion

Wastewater treatment plays an important role in protecting public health, protecting the environment, and ensuring the sustainable use of water resources by utilizing less energy. This review article has explored several aspects of wastewater treatment, including the importance of treatment processes, the environmental and public health implications by using untreated wastewater. The use of conventional and advanced treatment technologies, energy efficiency and resource recovery, decentralized systems, policy and regulatory frameworks, as well as challenges and future research directions in wastewater treatment. Wastewater treatment is fundamental for removing harmful contaminants and xenobiotic pollutants from wastewater, preventing the spread of waterborne diseases such as cholera, typhoid, diarrhoea, hepatitis, gastroenteritis, amebiasis, giardiasis, scabies, campylobacteriosis, and worm infections and safeguarding ecosystems. Conventional technologies, such as primary, secondary and tertiary treatments for wastewater treatment plants, while advanced technologies, including nanofibrous membrane filtration, advanced oxidation processes, electrochemical processes, microbial fuel cells (MFCs) and constructed wetlands, provide higher levels of treatment and resource recovery opportunities. Activated sludge is a by-product of secondary treatment, which can be utilized for the production of biofertilizers. Energy productivity and resource recovery are important aspects of sustainable wastewater treatment. The production of biogas through anaerobic digestion, recovering nutrients for reuse and utilizing bioelectrochemical systems, wastewater treatment plants can decrease energy consumption, generate renewable energy, and contribute to the circular economy. Decentralized wastewater treatment systems play vital role in flexibility, cost effectiveness, and resource recovery benefits, making them viable substitutes in areas with low population density or limited infrastructure. The addition of decentralized systems with conventional treatment plants can improve wastewater management and reduce environmental impacts. Policy, protocol and regulatory frameworks play vital role in guiding wastewater treatment practices, promoting sustainability, setting standards and providing economic encouragements for compliance and innovation. International standards, national regulations, and economic instruments drive sustainable wastewater management practices and ensure environmental protection. However, wastewater treatment still faces different challenges, such as the need for enhanced treatment efficiency, the presence of emerging contaminants and the bridging of the research-implementation gap. Future research should focus on developing technologies to address emerging contaminants, promoting resource recovery, optimizing treatment processes and enhancing climate change flexibility. Wastewater treatment is an evolving field that requires continued research, innovation, academic and industrial collaborations and teamwork to achieve sustainable and efficient solutions. The implementation of advancing technologies, solutions of emerging challenges, and sound policies, wastewater treatment can continue to protect public health, production of resources, preserve the environment, and contribute to the sustainable management of water resources.

Acknowledgement

I extend my sincere appreciation to my colleagues for their valuable contributions to this review article. Our collaborative effort has enriched the content, and their insights have significantly enhanced the quality of this work. I am grateful for the teamwork and shared commitment to producing a comprehensive and impactful review. This article is a product of our collective dedication.

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