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Wastewater treatment and resource recovery: Exploring the environmental and economic impacts

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Abstract

Approximately 80% of wastewater is discharged into the environment without adequate treatment, leading to ecosystem destruction. Studies have examined the use of wastewater treatment plants (WTPs) to tackle poor wastewater management and provision of clean and hygienically safe water globally. However, WTPs face significant challenges and are often ineffective at removing emerging contaminants. This study proposes an innovative and sustainable approach to the implementation of Water Resource Recovery Facilities (WRRFs), marking a transformative shift in water management and sustainability. WRRFs emphasize recovering and reusing valuable resources from wastewater, aiming to extract and repurpose water, nutrients, and energy. The objectives of the chapter are to highlights the potential for WRRFs to integrate with the circular economy, offering a forward-thinking approach to creating a more resilient and self-sustaining urban infrastructure. This transformation is crucial in addressing the challenges posed by population growth, climate change, and urbanization. It is hoped that policymakers and researchers will further consider the integration of WRRF concepts to enhance sustainability and resource efficiency.

Keywords Wastewater treatment plants, resource recovery, SDG 6, clean water and sanitation

1. Introduction

For decades, the primary focus of wastewater treatment has been on removing contaminants and pollutants to produce clean and safe water for various uses. However, the by-products generated during these treatment processes often end up in landfills or are discharged into the environment, posing significant environmental and economic burdens. Recently, a paradigm shift has occurred, recognizing wastewater as a valuable resource rather than a waste product. This is an innovative approach of transforming wastewater treatment into resource recovery, highlighting the environmental and economic benefits of implementation.

Wastewater is traditionally viewed as unwanted materials that must be treated and disposed to protect both the public health and environment. However, with dwindling natural resources, water utilities, engineers, and researchers have started to look at wastewater as valuable feedstock for resource and energy recovery. Wastewater contains useful resources such as water, nutrients, and energy which if recovered safely and effectively, can have economic and environmental benefits. Potable and non-potable water recovery from wastewater treatment gives an extra level of certainty and security to water supplies in the face of a changing climate.

Water contaminated with different concentrations of different heavy metals is unsuitable for use in any kind of agricultural or industrial activity. If such water is discharged into the environment directly, it may make entry into the plant system and pose a serious threat to the normal growth and development of plants. Some harmful effects of the intake of metallic water by humans include respiratory problems, arthritis, diarrhea, paralysis, vomiting and pneumonia (Mitra et al. 2022). Therefore, to make wastewater fits for sustainable application, it is subjected to treatments by different methods. See fig. 1a & 1b (Abuja WWTP)

The recovery of nutrients such as nitrogen and phosphorus and energy from wastewater emerges as another revenue for wastewater treatment plants. While water recovery has achieved an upward trajectory in both technology development and full-scale applications, the nutrient and energy recovery has recently received great attention from both scientific community and industrial stakeholders (Vu et al., 2022).

Wastewater contains important resources that could be recovered in wastewater treatment plants to generate value-added products such as renewable energy, bio-fertilizers and water for different purposes. The recycling of resources through innovative recovery processes is only a recent innovation in wastewater treatment systems and makes the processes of the treatment plants more efficient: reduces the amount of wastes and provides environmental and economic benefits.

In terms of resource utilization and sustainable development, valuable items (pollutant) in wastewater can be recovered through treatment to achieve resource utilization and increase the value of wastewater utilization. Activated sludge is a major portion of the treated wastewater residue. Most of the activated sludge is produced from wastewater treatment plants contains bio-solid including several organic and inorganic contaminants such as pesticides, pharmaceuticals, heavy metals, pathogens, bacterial biomass, surfactants, micro-plastics (MPs), and per-and poly-fluoroalkyl substances (Awasthi et al., 2022). Some activated sludge contains very high levels of contaminants and as such, cannot be used in agriculture. The treatment used for activated sludge includes aerobic digestion, anaerobic digestion, alkaline stabilization, thermal drying, disinfection, oxidation and stabilization (Collivignarelli et al., 2019).

Activated sludge typically contains 15 – 90 % solids. Therefore, it contains a low amount of water as compared to sludge (Awasthi et al., 2022). Activated sludge obtained from wastewater treatment contains various substances except pathogen. It contains several inorganic nutrients. Thus, it can be applied to agricultural land as a good source of nutrition (Kelly et al., 2011). In addition, it also contains carbohydrates, proteins and other organic components. Therefore, it may be used for some nutritional products. Based on AS origin in the wastewater, they can be categorized in different five types. These include dried AS, stockpiled AS, lagoon AS, non-digested AS and digested AS (Liu et al., 2020).

A huge quantity of AS is generated from municipal solid wastewater treatment plants. Wastewater treatment plants are the source of all major pollutants such as personal care products, pharmaceuticals, polybrominated diphenyl ethers (PBDEs), and per- and polyfluorinated alkyl substances (PFASs) (O'Keeffe & Akunna, 2022). Fig. 1 presents the composition and concentration of various components in AS generated by a water treatment plant, AS utilization and composition (Azuara et al., 2015; Kelly et al., 2011). The dewatered bio-waste contains a high amount of moisture which makes it a favorable substrate for anaerobic digestion. The anaerobic digestion is useful for energy generation. Anaerobic process takes place at the intersection of dewatering and AS thickening (Gikas, 2017).

2. Wastewater

Wastewater produces from several anthropogenic activities is a complex mixture containing organic compounds, inorganic compounds and pathogens such as bacteria, fungi and viruses (Varghese et al., 2020). However, hospital wastewater is relatively different compared to the domestic wastewater. It contains disinfectants, antibiotics, and antibiotic resistance bacteria (Voigt et al., 2020). Industrial wastewater contains industrial wastes such as petrochemical, food processing chemical, electronic and electrochemical. Industrial wastewater contains a high amount of heavy metals which is of serious concern (Azimi et al., 2017).

Wastewaters consist of two components, treated water and sludge. Treated water has a variety of migration routes, such as ocean, surface water, groundwater and deep Wells. The sludge produced is a complex mixture and it cannot be disposed of without treatment. Therefore, the produced sludge is treated before its disposal to landfill or soil (Bisognin et al., 2020). Sludge contains a higher proportion of liquid (97%) and low concentration of solid 3%. Sludge is treated and is gone through several processes which reduce the pathogen.

Advanced wastewater treatment methods are membrane bioreactor (MBR) bio-reaction technology and A2/O process technology (Nadeem et al., 2022; Lu et al., 2022). However, the concept of wastewater treatment is only limited to the removal of pollutants from wastewater, which leads to the waste of a large amount of usable materials in wastewater. From the viewpoint of resource utilization and sustainable development, human beings need to utilize the pollutants in wastewater that are of use to human beings, because such treatment can achieve resource utilization and increase the value of wastewater utilization.

Regarding nutrient recovery, it provides sustainable use of phosphorus (Sarvajayakesavalu et al., 2018), produces a high-quality effluent with low phosphorus concentration, which mitigates eutrophication risks in water bodies as well as produces an alternative source of fertilizer, alleviating phosphate rock reserves (Chrispim et al., 2020). Regarding eutrophication, (Shahid et al. (2017) estimated the amount of phosphorus compounds flowing from agriculture and domestic wastewater and concluded that India, China, Brazil and USA will be the countries with the largest flows of phosphorus by 2100. A promising solution for wastewater treatment systems is energy recovery, since wastewater contains chemical, thermal and hydraulic energies. In a conventional wastewater treatment plant, it is possible to recover energy in the effluent treatment or in the sludge line to supply at least a substantial part of the wastewater plant's energy demand (Đurđević et al., 2019). The ultimate aim would be for the plant to become energy self-sufficient with zero external energy supply (Garrido et al., 2013) As there is substantial energy consumption during several stages of the treatment (sewage collection, transportation, effluent treatment, sludge treatment and disposal).

3. Wastewater treatment plants

Water scarcity poses a serious threat to the development of human societies hence, wastewater reclamation and reuse is considered to be the best strategy for meeting current and future water needs of water. On the other hand, water pollution represents an especially dangerous problem in developing countries. In recent years, economic development has accelerated and public and governmental consciousness of environmental protection has grown leading to rapidly increase capacity for sewage treatment.

Wastewater treatment consists of primary, secondary, and sometimes advanced treatment processes, with different biological, physical, and chemical technologies. At present, many sewage treatment processes are used in wastewater treatment plants (WWTPs), including conventional activated sludge treatment, anaerobic-anoxic-oxic (A2/O), anaerobic-oxic (A/O), sequencing batch reactor (SBR), and oxidation ditch. The treatment efficiency of a WWTP is related to the process and also depends on the scale of the WWTP (Dinko et al., 2016).

The energy sufficiency of WWTPs is now becoming a topic of interest because sustainable supplies of both water and energy and corresponding carbon emission are critical for urban development. The water–energy nexus has already become a hot topic in current policy research prompting a series of studies on the relationship between energy and water for sustainable development. With the increasing attention to climate issues, conserving energy, improving energy efficiency and seeking alternative energy sources have become a common pursuit of global sustainable development. WWTP is a typical case of interactions between water and energy.

In most WWTPs, water quality is improved at the expense of significant energy input. WWTPs are frequently recognized as the largest independent energy consumers managed by municipalities. Most major stages in WWTP, such as the collection and conveyance of wastewater, physical and chemical treatment, biological treatment, sludge treatment and discharge, require considerable energy. In a conventional WWTP, 25%–40% of operating costs are attributed to energy consumption. Moreover, corresponding greenhouse gas emissions by energy consumption in WWTPs also causes global concern.

Biological wastewater treatment plants (WWTPs) have been employed throughout the world to treat municipal wastewater. Despite the fact that it is efficient in removing organics, large amounts of excess sludge are generated. The average annual production of excess sludge is 3 million wet tons in Australia, and 240 million wet tons in Europe, USA and China combined (Wang et al., 2023). The main methods for sludge disposal have been and still are landfill, agricultural use and incineration, all incurring very large costs. Therefore, reducing sludge production in WWTPs has become a hot topic for both practitioners and researchers.

The excess sludge can be classified into primary sludge and secondary sludge (or waste activated sludge, i.e. WAS) Primary sludge is the sludge composed of settleable solids removed from raw wastewater in primary settler. WAS is the sludge produced by biological process such as activated sludge process. WAS mainly consists of bacteria growing on organic and inorganic substances, extracellular polymeric substances (EPS) excreted by bacteria, recalcitrant organics originating from wastewater or formed during bacterial decay, and inorganic from wastewater. In general, the biodegradability of primary sludge is high compared to WAS which has low biodegradability (Wang et al., 2023).

Lots of technologies have been developed to reduce WAS production. The technologies for achieving sludge reduction can be divided into two types, (a) reducing sludge production in wastewater treatment line, and (b) achieving sludge reduction in sludge treatment line.

In general, they are not implemented simultaneously in the same WWTP. For instance, reducing sludge production in wastewater treatment line is applied in the small WWTPs where anaerobic digesters do not exist, whereas achieving sludge reduction in sludge treatment line is implemented in the large WWTPs with anaerobic digesters.

The commonly used approach for reducing sludge production in wastewater treatment line is to implement technologies to treat return activated sludge, which is then re-circulated to the main-stream bioreactor for further biodegradation. These treatment technologies include chemical treatment, mechanical treatment, thermal treatment and electrical treatment. They cause cell lysis with subsequent release of intracellular and extracellular substances, which become substrate available for biodegradation, whereby sludge reduction is achieved. In addition to the treatment technologies, the other technologies for reducing sludge production in wastewater treatment line include addition of chemical un-coupler, and predation of protozoa and metazoa.

In the sludge treatment line, sludge is subject to thickening, stabilization, dewatering and final disposal. Anaerobic digestion is the most commonly used sludge stabilization method, which is used to reduce the mass of sludge. However, anaerobic digestion is generally limited by the poor biodegradability of WAS and thus, analogous to the technologies applied in wastewater treatment line. A number of pre-treatment technologies have been integrated into the sludge treatment line before anaerobic digestions to achieve sludge reduction (P2 in Fig. 1). They include physical pre-treatment, chemical pre-treatment and biological pre-treatment. Although sludge reduction technologies have been documented, the state-of-the-art technologies and treatment process design for reducing sludge production have not been reviewed.

4. Potential drawbacks of wastewater treatment plants

The rapid growth of the industries and population leads to increasing generation of industrial and municipal wastewater. This wastewater threatens directly or indirectly the human health and industrial processes. Therefore, it is necessary to develop a rapid, simple, eco-friendly, effective, and efficient method for eliminating pollutants from industrial and municipal wastewater. The wastewater treatment aims to remove pollutants including particles, organic/inorganic substances, and pathogenic microorganisms, and finally returned to the cycle (Crini and Lichtfouse,, 2019; Matesun et al., 2024).

4.1 High operating cost

Wastewater treatment plants are often associated with high operating costs due to their significant energy consumption, the need for a large workforce, and the requirement for regular maintenance to ensure optimal performance. For instance, while trickling filters are highly efficient in removing biochemical oxygen demand (BOD), treating large volumes of organic matter, and effectively eliminating ammonia gas with minimal sludge production, they come with the downside of high operational expenses and the generation of substantial odors. Similarly, the electro-dialysis method, known for its precise ion selectivity, also faces the challenge of elevated operational costs. Moreover, the global shift away from fossil fuels adds to the complexity of cost management, as these energy sources are still heavily relied upon in many treatment facilities.

4.2 Concern about damage to the environment

Environmental concerns surrounding wastewater treatment plants stem from the generation of significant waste and potentially harmful by-products that can adversely affect ecosystems. One of the primary by-products is sludge, which, if not properly treated or disposed of, can contaminate soil and water bodies, leading to long-term environmental degradation. Additionally, wastewater plants often emit noise pollution and unpleasant odors, which can cause discomfort, nausea, and health risks for nearby residents.

Air pollution is another issue, as treatment processes can release greenhouse gases such as methane and carbon dioxide, contributing to global warming. Chemical pollutants, including micro-pollutants like pharmaceuticals and heavy metals, may not be fully removed during treatment and can be released into rivers and lakes, posing threats to aquatic life and disrupting ecosystems. The cumulative impact of these factors can result in harm to local flora and fauna, reducing biodiversity and destabilizing natural habitats.

Furthermore, the heavy reliance on non-renewable energy sources in many wastewater plants exacerbates environmental concerns, as the use of fossil fuels contributes to carbon emissions. Balancing the need for effective wastewater treatment with the protection of the surrounding environment is a growing challenge that requires more sustainable solutions and innovation in treatment technologies (Hao and Wang, 2019).

4.3 Growth of pathogens

The growth of pathogens poses a significant risk when treated wastewater is discharged into the environment, as residual and persistent pathogens can remain in the effluent. These microorganisms, if not fully eliminated, have the potential to regenerate and proliferate, leading to harmful environmental and public health impacts. While disinfection methods, such as chlorination, are commonly used to combat these pathogens, they come with their own drawbacks. Chlorine, though effective at killing bacteria and viruses, is a corrosive chemical that can have adverse effects on both infrastructure and ecosystems. Moreover, the ingestion or exposure to chlorine by-products, such as trihalomethanes, poses health risks, including respiratory problems and potential carcinogenic effects. This underscores the need for more effective and less harmful disinfection techniques to ensure the safe release of treated wastewater (Xiao et al., 2024).

4.4 Regulatory constraints on land

Regulatory constraints on land and space usage pose significant challenges for the establishment of wastewater treatment plants, as these facilities typically require substantial areas to operate effectively. Land-use regulations vary widely across regions, which can complicate the sitting and expansion of such plants, particularly in densely populated or environmentally sensitive areas. For example, technologies like Rotating Biological Contactors (RBC), though cost-effective in terms of operation and known for producing minimal sludge, demand a considerable amount of space for installation and operation. This land requirement often conflicts with local land use laws, environmental protections, and competing land uses, such as agriculture, residential developments, or conservation efforts. Additionally, the proximity of treatment plants to residential areas may face resistance from communities due to concerns over odors, noise, and potential environmental impact. Addressing these regulatory and spatial challenges requires innovative design approaches, such as compact and modular systems, that reduce land usage while adhering to local environmental and zoning laws (Saidur et al., 2023).

4.5 Sludge management

Sludge management is a significant challenge in wastewater treatment, posing substantial environmental and health risks. Sludge, often laden with toxic substances, pathogens, and heavy metals, requires careful handling and disposal to prevent contamination of soil, water bodies, and ecosystems. Coagulation, while an effective and low-cost method for removing contaminants from wastewater, produces large volumes of sludge, creating a bottleneck in the treatment process. The accumulation of sludge not only increases operational costs due to storage, transport, and disposal requirements but also presents serious health hazards if not properly treated.

Improper sludge management can lead to the release of harmful substances into the environment, contaminating natural resources and affecting both human and animal health. Advanced methods such as anaerobic digestion or thermal treatment can reduce sludge volume and even recover valuable by-products like biogas or fertilizer. However, these methods are often costlier and require more sophisticated infrastructure. The key to addressing sludge-related challenges lies in developing integrated solutions that minimize sludge generation, enhance resource recovery, and ensure safe, environmentally responsible disposal (Qrenawi and Rabah, 2021).

4.6 Problem associated with acceptance by the community

Community resistance to the sitting of wastewater treatment plants is a significant challenge, driven by concerns about potential health risks, environmental impact, and quality of life. Residents often oppose the proximity of these facilities due to fears of unpleasant odors, noise pollution, potential contamination, and the general stigma attached to wastewater treatment. The perception of wastewater plants as hazardous or disruptive makes communities wary, fostering a *not in my backyard* mindset (Padilla-Rivera et al., 2016).

In many cases, the lack of transparent communication about the safety measures, environmental protections, and technological advancements employed in modern treatment plants further exacerbates this resistance. Communities are often unaware of innovations that mitigate odors, noise, and risks, or the critical role these facilities play in protecting public health and the environment. Additionally, concerns about declining property values and the aesthetic impact of large industrial structures contribute to the opposition.

To overcome these challenges, proactive engagement with local communities is essential. This includes educating the public about the benefits of wastewater treatment, addressing their concerns through open dialogue, and demonstrating the use of advanced technologies that minimize nuisances and environmental risks. Involving the community in the planning process and offering incentives, such as green spaces or community benefits, can also foster greater acceptance of wastewater treatment plants. The key word to the community acceptance of the wastewater treatment plant in their neighborhood is inclusivity.

4.7 High cost of modern equipments and technology

The high cost of modernizing wastewater treatment plants is a significant barrier to efficient and safe operations. Many existing facilities are outdated, operating with aging equipment that not only reduces treatment effectiveness but also contributes to various operational hazards, such as noise pollution, leakages, and unpleasant odors. Upgrading these plants to incorporate modern technology is essential for improving efficiency, reducing environmental impact, and ensuring regulatory compliance. However, the financial burden of acquiring and installing advanced equipment, such as energy-efficient aeration systems, odor control technologies, and automated monitoring systems, is a major challenge, especially in today's economic climate (Rathore et al., 2022).

These modernization efforts require substantial capital investment, making it difficult for many municipalities or private operators to afford the upgrades without significant financial support. Additionally, the high maintenance costs of cutting-edge technology further strain operational budgets. Without these updates, plants may continue to operate inefficiently, leading to environmental hazards, community complaints, and costly repairs from frequent breakdowns (Sureyya et al., 2020).

To address this issue, governments and industry stakeholders need to explore innovative financing models, such as public-private partnerships (PPPs), green bonds, or grants that support sustainable infrastructure. Implementing phased modernization, where the most critical components are upgraded first, can also help distribute costs over time. Investing in modern, energy-efficient technologies may also offer long-term savings through reduced energy use and lower operational costs, making the upfront investment more justifiable (David et al., 2022).

5. Transition to water resource recovery facilities

The transition from traditional wastewater treatment plants to Water Resource Recovery Facilities (WRRFs) marks a paradigm shift in how we approach wastewater management. Unlike conventional plants that focus solely on treating and disposing of wastewater, WRRFs emphasizes the recovery and reuse of valuable resources contained within the waste stream. These facilities are designed to not only purify water but also to extract energy, nutrients, and other materials such as bio-solids and biogas, turning waste into a resource.

This innovative approach supports sustainability goals by reducing environmental impact, conserving resources, and creating economic opportunities. As global challenges like water scarcity, climate change, and energy demands intensify, the move towards WRRFs reflects the need for a more circular and resilient approach to water and resource management (Frago et al., 2021).

The concept of the circular economy is gaining global traction, especially in the wastewater sector, with a focus on transforming wastewater into valuable resources. Water Resource Recovery Facilities (WRRFs) play a pivotal role in this vision by converting wastewater into renewable energy, clean water, nutrients, and bio-based materials. By treating wastewater not as a waste product but as a source of recoverable resources, WRRFs directly support a circular economy model. This approach maximizes resource efficiency, reduces environmental impact, and promotes sustainability by creating closed-loop systems where waste is continually repurposed into valuable products (Mannina et al.,2021).

5.1 Water Reuse and Recycling

Water reuse and recycling are integral components of water resource recovery, transforming treated wastewater into a valuable resource for diverse applications, including potable water, industrial processes, and irrigation. By safely reusing treated water, communities can significantly reduce their dependence on freshwater sources and enhance overall water sustainability.

To facilitate this process, an efficient and well-designed collection system is crucial. Such systems typically incorporate a range of infrastructure components, including underground pipelines, manholes, gravity-fed pipes, lift stations, and force mains. These elements work together to transport wastewater from various sources to the water resource recovery facilities where it is treated and repurposed. Additionally, maintenance structures ensure the reliability and functionality of the collection system, addressing potential issues and minimizing disruptions. Implementing advanced collection and conveyance technologies can further enhance the efficiency and safety of water reuse and recycling initiatives, supporting the sustainable management of water resources (Florides et al., 2024).

5.2 Energy Generation

Water Resource Recovery Facilities (WRRFs) offer significant potential for energy generation through various advanced technologies. These facilities can harness the energy contained in wastewater by utilizing biogas production, fuel cells, and other cutting-edge methods. Biogas, generated from the anaerobic digestion of organic matter in wastewater, can be captured and converted into renewable energy, providing a sustainable power source for facility operations or even for the local grid. Additionally, WRRFs can incorporate fuel cells, which efficiently convert chemical energy from wastewater into electricity with minimal emissions. By integrating these innovative energy recovery technologies, WRRFs not only enhance their operational sustainability but also contribute to broader energy conservation and greenhouse gas reduction goals (Qipeng et al., 2022).

5.3 Recovery of useful Nutrient

The recovery of valuable nutrients from wastewater is crucial for addressing the environmental challenges posed by nutrient pollution, such as eutrophication. Excessive nutrient loads, particularly phosphorus and nitrogen, contribute to harmful algal blooms, which can severely degrade aquatic ecosystems and impact recreational, food, and drinking water sources. The effects of climate change, including rising water temperatures and increased frequency of severe storms, can exacerbate these issues by reducing oxygen levels in water and enhancing nutrient runoff from land to water bodies.

Water Resource Recovery Facilities (WRRFs) are instrumental in mitigating these impacts by efficiently recovering and recycling nutrients from wastewater. Advanced treatment technologies enable the extraction of nutrients like phosphorus and nitrogen, which can then be transformed into valuable fertilizers. This process not only reduces the environmental impact of nutrient discharge but also supports sustainable agricultural practices by providing a source of recycled nutrients. By integrating nutrient recovery into their operations, WRRFs help close the loop in the nutrient cycle, contributing to improved water quality and reducing the ecological and economic consequences of nutrient pollution (Yuanyan et al., 2020).

5.4 Management of Biosolids

Water Resource Recovery Facilities (WRRFs) play a crucial role in the management and utilization of Biosolids, which are nutrient-rich by-products generated during wastewater treatment. These facilities are equipped to process biosolids into high-quality products that can be used as fertilizers or soil amendments, contributing to sustainable agriculture and land management.

In an activated sludge treatment plant, wastewater undergoes a sophisticated filtration and biological treatment process within large tanks, designed to mimic natural systems for effective organic material removal. This process not only produces clean, recycled water but also yields biosolids that are rich in essential nutrients. The treated biosolids are then carefully managed and processed to meet regulatory standards, ensuring their safety and effectiveness. Once processed, these biosolids are applied to designated land areas as a valuable resource, enhancing soil fertility and promoting healthy plant growth. By converting wastewater by-products into beneficial soil amendments, WRRFs support circular economy principles and reduce reliance on synthetic fertilizers, while also contributing to environmental sustainability (Elgarahy, et al., 2024).

5.5 Modular, Adaptive and Decentralized water infrastructures

Wastewater treatment systems today vary widely in scale and design, from conventional low-cost facilities to large, expensive centralized systems, as well as smaller, decentralized setups. Decentralized systems are typically stand-alone or clustered facilities that serve local communities, offering the advantage of onsite treatment using both anaerobic and aerobic methods. Aerobic modules often include horizontal planted gravel filters and polishing ponds, while anaerobic modules consist of baffle reactors, settlers, and anaerobic filters (Stoler et.al., 2022).

Modular, adaptive, and decentralized water infrastructures utilize cutting-edge technologies to enhance flexibility and efficiency. Examples of these innovations include next-generation ultra-filtration systems, mobile water treatment units, atmospheric water capture technologies, and container-based systems. These decentralized models offer scalable solutions that can be tailored to various applications, promoting sustainable and resilient water management. To fully realize the benefits of these systems, a justice-oriented approach is essential, ensuring that all communities have access to safe, reliable, and affordable water resources. By incorporating these advanced technologies into a modular and adaptable framework, Water Resource Recovery Facilities (WRRFs) can address diverse needs while supporting equitable water access and sustainability (Amber et al., 2023).

5.6 Integration with Circular Economy Principles

Integrating Water Resource Recovery Facilities (WRRFs) with circular economy principles is a powerful approach to sustainable water management. By employing advanced physical and chemical treatment processes, WRRFs can treat used wastewater to a quality suitable for various forms of reuse. This creates a closed-loop system where wastewater is effectively recycled and repurposed, significantly reducing the need for additional freshwater resources.

In a circular economy model, WRRFs play a crucial role by not only treating wastewater but also recovering valuable resources such as energy, nutrients, and biosolids. By closing the loop on water and resource management, these facilities contribute to a more sustainable and efficient system. This approach minimizes waste, reduces environmental impact, and supports the broader goals of resource conservation and sustainability. Through their integration with circular economy principles, WRRFs help create resilient and resource-efficient communities, turning wastewater challenges into opportunities for resource recovery and reuse (Morseletto et al., 2022).

5.7 Advanced Technologies and Innovations

Water Resource Recovery Facilities (WRRFs) are at the forefront of utilizing advanced technologies and innovations to enhance wastewater treatment and resource recovery. These facilities increasingly deploy state-of-the-art technologies, including membrane bioreactors, advanced oxidation processes, and nanotechnology, to achieve higher levels of purification and efficiency.

Emerging environmentally sustainable treatment methods such as electro-coagulation and biopolymers, along with innovative approaches like catalytic media and advanced side stream filtration, are transforming the capabilities of WRRFs. This progress signifies a significant leap towards achieving near-pristine water quality, demonstrating that advanced treatment solutions are making the vision of clean, high-quality water more attainable than ever before (Zamathula et al., 2024).

5.8 Regulatory Frameworks and Policy Support

The successful transition to Water Resource Recovery Facilities (WRRFs) hinges on the establishment of robust regulatory frameworks and supportive policies that promote resource recovery and sustainability. Water service regulation varies widely across countries, encompassing aspects such as water quality, service delivery, network infrastructure, and other critical factors. In many regions, the development of dedicated regulatory bodies for drinking water and wastewater services has emerged as a key strategy to address the complexities of water management and ensure effective oversight.

Despite this progress, many countries and territories are still in the process of establishing or strengthening their water regulatory frameworks. Dedicated water regulators, when compared to those in other utility sectors, are often less developed. Regulatory functions in the water sector encompass a broad spectrum of activities, including setting and monitoring standards for access and quality, determining tariffs, establishing efficiency incentives, gathering data, and overseeing performance. Additionally, engaging users and stakeholders in the regulatory process is crucial for creating responsive and effective water management systems. To fully realize the benefits of WRRFs, it is essential to advance these regulatory frameworks and policies to support the innovative and sustainable management of water resources (Chrispim et al., 2020).

5.9 Public Education and Awareness

Raising public awareness and fostering understanding of the benefits of Water Resource Recovery Facilities (WRRFs) is essential for garnering community support and acceptance. Effective public education campaigns should highlight the key advantages of WRRFs, including their role in sustainable water management, resource recovery, and environmental protection.

Communicating the positive impact of WRRFs on water quality, energy generation, nutrient recovery, and the reduction of waste can help dispel misconceptions and build trust. Engaging the public through informational workshops, educational programs, and transparent dialogue about the technologies and processes involved can enhance community confidence and support. Additionally, showcasing successful case studies and demonstrating tangible benefits, such as improved local water quality and reduced environmental impact, can further strengthen public support. By fostering an informed and engaged public, we can ensure the successful implementation and operation of WRRFs, leading to more resilient and sustainable water management systems (Wapwera and Akintunde. 2022: Kola-Olusanya, 2024).

5.10 Removal of harmful organisms

Water Resource Recovery Facilities (WRRFs) are designed to effectively remove harmful organisms, pathogens, and other contaminants from wastewater and storm-water, ensuring that treated water can be safely discharged into natural water bodies. For example, in Muscatine, Iowa, wastewater is treated at a WRRF before being released into the Mississippi River, significantly reducing the risk of water pollution and protecting the ecosystem.

Through advanced treatment processes, including biological, chemical, and physical methods, WRRFs eliminate bacteria, viruses, and harmful chemicals, transforming wastewater into safe, clean water. This process not only helps maintain the health of aquatic environments but also protects public health by preventing the contamination of water sources used for drinking, recreation, and agriculture. By removing these harmful organisms and pollutants, WRRFs play a critical role in preserving water quality and supporting sustainable water management.

6. Conclusion

The shift from traditional wastewater treatment to resource recovery represents a fundamental rethinking of how society manages its water and waste streams. Wastewater is no longer seen as a byproduct to be managed and discarded but instead, it is a valuable resource from which water, energy, nutrients, and other materials can be extracted. The environmental and economic benefits of this transformation are profound. By integrating energy-efficient processes, nutrient recovery systems, and water reuse technologies, Wastewater Resource Recovery Facilities (WRRFs) offer solutions that align with the principles of sustainability and the circular economy.

From an environmental perspective, resource recovery reduces the depletion of natural resources, mitigates pollution, and lowers greenhouse gas emissions. Recovering energy from wastewater, for example, reduces reliance on fossil fuels, while the recycling of nutrients such as phosphorus and nitrogen helps prevent eutrophication and decreases the need for synthetic fertilizers. Water reuse strategies, especially in regions facing water scarcity, provide an alternative supply that can alleviate pressure on freshwater sources.

Economically, WRRFs reduce operational costs by turning waste into value-added products like biogas, biosolids, and reclaimed water. These products can create new revenue streams and improve the financial viability of wastewater facilities, enabling communities to reinvest in infrastructure and further enhance sustainability. Moreover, the adoption of smart technologies such as advanced process control and digital twins improves efficiency, reduces maintenance costs, and optimizes resource management.

However, the implementation of resource recovery systems requires overcoming technical, financial, and regulatory barriers. The transition must be supported by robust policies, adequate funding mechanisms, and stakeholder engagement to maximize its potential. As technologies mature and become more cost-effective, widespread adoption of resource recovery practices will be critical to meeting future environmental and economic challenges.

Ultimately, transforming wastewater treatment into a resource recovery paradigm is not just a technical innovation, it is a critical step toward creating more resilient, sustainable, and equitable systems that benefit both society and the planet. This chapter has highlighted the substantial impacts of this transformation, illustrating the powerful synergies between environmental stewardship and economic opportunity. Moving forward, resource recovery will play a pivotal role in shaping a sustainable future for wastewater management.

Declarations

Data availability Data will be made available upon reasonable request.

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