



Wastewater Treatment and Reuse: Correlation, Impact, and Critical Human Health Challenges

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Abstract

Background: Wastewater treatment and reuse are crucial for sustainable water management, addressing global challenges such as water scarcity, environmental pollution, and public health risks. As industrialization and population growth intensify water demand, advanced wastewater treatment technologies provide sustainable solutions for water reuse and resource recovery. This study explores the economic and environmental benefits of wastewater treatment, emphasizing its role in transforming waste into potable water, renewable energy production, and minimizing ecological degradation. **Results:** Modern wastewater treatment technologies, including membrane filtration, advanced oxidation processes (AOPs), electrochemical treatment, and microbial fuel cells (MFCs), significantly improve pollutant removal and water quality. Additionally, energy recovery through anaerobic digestion and hydrothermal carbonization enhances the circular economy by converting organic waste into bioenergy. The study identifies emerging innovations such as artificial intelligence (AI)-driven optimization, decentralized treatment systems, and sustainable infrastructure as key

developments that enhance treatment efficiency and resilience. Despite these advancements, regulatory frameworks and public health guidelines remain crucial for ensuring safe wastewater reuse, particularly in mitigating the risks associated with heavy metals, pharmaceuticals, and antibiotic-resistant microorganisms. **Conclusion:** While wastewater treatment presents a viable strategy for environmental sustainability, its implementation is hindered by operational costs, infrastructural limitations, and regulatory challenges. Addressing these issues requires a comprehensive approach integrating technological advancements, policy interventions, and public engagement. Sustainable wastewater management can significantly improve global water security, environmental conservation, and economic stability by shifting wastewater from a waste byproduct to a valuable resource.

Keywords: Wastewater treatment, Human health, Sustainable water management, Environmental, sustainability, Circular economy

Introduction

Water is a vital resource for human existence, economic progress, and ecological equilibrium. Rapid population growth, industrialization, and climate change have severely taxed global freshwater supplies, prompting the urgent development of

Significance | This study emphasizes the significance of wastewater treatment in sustainability, water security, environmental preservation, human health safeguarding and resource recovery.

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sustainable wastewater treatment and reuse techniques (Mithun et al., 2024). Ineffective wastewater treatment intensifies water shortage in several areas, leading to environmental deterioration and significant human health issues (Deviprasad et al., 2023). Treating and reusing wastewater is a practical solution to address these important problems. It helps reduce pollution and protects natural water sources (Nazma et al., 2023a). Wastewater comes from homes, farms, and factories and contains a mix of harmful substances, germs, and new pollutants. The absence of effective wastewater treatment systems is associated with significant health hazards, such as waterborne illnesses, endocrine disturbances, and antibiotic resistance (Sunny et al., 2021). Global health estimates indicate that unclean water and inadequate sanitation result in around 1.8 million fatalities per year, predominantly in low-income and developing countries. The World Health Organization (WHO) emphasizes the necessity for comprehensive wastewater treatment systems to provide safe water supplies and reduce health hazards. The connection between wastewater treatment, human health, and environmental sustainability requires a thorough comprehension of diverse treatment methods, their effectiveness, and their reuse uses (WHO, 2020).

Wastewater reuse is increasingly acknowledged as a crucial approach in water resource management, especially in dry and semi-arid areas with constrained freshwater availability. Reclaimed water is progressively employed for agricultural irrigation, industrial cooling, and even potable reuse in sophisticated treatment systems (Nazma et al., 2023b; Ifty et al., 2023a). The possible benefits of recycling wastewater are hindered by significant challenges, including technology issues, cost concerns, government rules, and public opinion. To make sure treated wastewater meets strict safety rules, we need better treatment methods to remove harmful substances like heavy metals, drug leftovers, and microplastics that current methods often miss (Ghaudenson et al., 2021).

Table 1 presents a comparative review of conventional water treatment systems, emphasizing their efficacy in eliminating significant contaminants and pathogens, their associated costs, and their typical uses. This comparison highlights the necessity for sophisticated treatment technology to successfully tackle emerging pollutants.”

From a public health perspective, poorly managed wastewater containing harmful substances like persistent organic pollutants (POPs), antibiotic-resistant bacteria (ARBs), and viral infections can pose serious risks. Notwithstanding technical progress, deficiencies in wastewater management endure, especially in low-income areas where infrastructure and financial resources are insufficient. A comprehensive strategy for wastewater treatment must consider local socio-economic and environmental factors to ensure sustainability and efficacy (Nazma et al., 2022).

Conventional wastewater treatment techniques, including sedimentation, filtration, and chlorination, have historically been employed to enhance water quality. However, these technologies often struggle to remove certain pollutants, like medicines, chemicals that affect hormone balance, and emerging tiny pollutants. New treatment methods, such as membrane bioreactors (MBRs), advanced oxidation processes (AOPs), and bio electrochemical systems, have been developed to enhance wastewater cleaning and enable reuse.

The release of untreated or insufficiently treated effluent into natural water bodies has significant environmental repercussions. Too many nutrients in wastewater can lead to eutrophication, which causes harmful algal blooms, low oxygen areas, and damage to water habitats. Heavy metals, harmful chemicals, and leftover medicines build up in sediments and water animals, causing long-lasting environmental problems. Moreover, microplastics originating from industrial and residential sources permeate food chains, heightening worries over their effects on marine organisms and human health (Aleem et al., 2003; Rice et al., 2012). Contaminated wastewater is a significant conduct for waterborne illnesses, such as cholera, typhoid, and hepatitis, from a human health standpoint. More bacteria in wastewater are becoming resistant to antibiotics, making it harder to treat infections. This is a growing problem for public health efforts around the world because common antibiotic treatments are not working as well. Understanding how wastewater treatment affects the presence of harmful germs and public health is important for creating effective solutions. Efficient wastewater management needs strong regulatory frameworks and proactive public involvement. Numerous nations have implemented rigorous regulations for wastewater disposal and reuse, conforming to criteria established by entities such as the WHO, the Environmental Protection Agency (EPA), and the European Environment Agency (EEA). Nonetheless, variations in regulatory enforcement and monitoring capacity lead to variances in global wastewater treatment techniques. The public's opinion and acceptability of wastewater reuse significantly influence its implementation. Although modern treatment techniques ensure its safety, psychological and cultural obstacles frequently prevent communities from adopting treated wastewater for drinkable purposes. Education, clear messaging, and supportive laws are important for changing how people view wastewater reuse and encouraging more use of circular water management systems. Dealing with the complicated problems of wastewater treatment and reuse requires a clear plan that includes improving technology, changing regulations, and getting the community involved. Governments, companies, and researchers must cooperate to provide economical and scalable treatment options while maintaining adherence to regulations and safeguarding public health. The shift to a circular water economy

requires investments in decentralized wastewater treatment facilities, resource recovery projects, and nature-based solutions (Allen et al., 2010). Rainwater harvesting, greywater recycling, and phytoremediation techniques exhibit sustainable methods that enhance conventional wastewater management strategies. Furthermore, data-driven monitoring and AI-based predictive analytics are becoming essential tools for optimizing wastewater treatment operations and reducing hazards. As water scarcity increases and global environmental issues worsen, the necessity for sustainable wastewater treatment and reuse becomes increasingly evident (Ifty et al., 2023b). Through the integration of scientific developments, legal frameworks, and public engagement, wastewater may be converted from a byproduct into a useful resource, enhancing water security, environmental conservation, and public health outcomes.

2. Methodology

This study uses comprehensive literature analysis to examine the correlation between wastewater treatment, environmental sustainability, and public health. A thorough examination was performed on peer-reviewed journals, government papers, and international regulatory documents to assess current wastewater treatment methods, their effectiveness, and their socio-economic consequences. The selection criteria emphasized papers published over the last ten years that investigate wastewater treatment methods, energy recovery techniques, wastewater reuse applications, and regulatory frameworks. The focus was on sophisticated treatment methods, including membrane filtration, advanced oxidation processes, electrochemical treatments, and microbial fuel cells. The analysis looked at laws, costs, and new trends in AI-based wastewater management to provide a complete picture of the future of wastewater treatment. We compared traditional and new treatment methods to understand their benefits, drawbacks, and costs. The research incorporated case studies from places with successful wastewater reuse efforts to offer practical insights into implementation problems and best practices. This study looks closely at how treating wastewater can help reduce water shortages, control pollution, and recover energy. It focusses on recent scientific findings and new laws.

3. Correlation Between Wastewater Treatment and Human Health

The connection between efficient wastewater treatment and human health is critically important. As urban populations grow and industrial activity escalates, the pressure on current wastewater treatment systems intensifies, heightening the danger of waterborne infections in communities. Advanced wastewater treatment methods are essential for decreasing pathogen levels in water and

minimizing the discharge of hazardous chemicals and heavy metals into the environment; therefore, they enhance public health results. Comprehensive studies demonstrate a significant relationship between enhanced wastewater treatment and a decrease in health problems, including gastrointestinal disorders and skin infections. Improved treatment methods substantially reduce pathogen levels in wastewater, which is crucial for safeguarding public health. Studies show that secondary and tertiary treatment methods can reduce virus levels by more than 84%, which helps lower the risk of waterborne diseases (Juraev et al., 2022; Tzanakakis et al., 2023). Moreover, sophisticated treatment methods are essential in reducing the detrimental health effects of water pollution, which is linked to ailments such as dermatological conditions and gastrointestinal illnesses. In cities, studying wastewater has become a key tool for monitoring health trends and the presence of germs, giving us valuable information about the health of the community. The proper deployment of wastewater treatment systems is crucial for protecting public health and decreasing disease prevalence.

Environmental health significantly influences this association. The insufficient management of wastewater leads to the pollution of aquatic environments, especially by the discharge of microplastics (MPs) and emerging contaminants (ECs). Research indicates that wastewater treatment facilities (WWTPs) frequently inadequately eliminate these contaminants, leading to their release into natural water bodies. The lack of sophisticated treatment technology intensifies this problem, highlighting the necessity for enhanced wastewater management techniques to reduce environmental health concerns. Confronting these difficulties with new and sustainable wastewater treatment techniques will be essential for maintaining ecological integrity and safeguarding human health.4. Results and discussion:

4. Impact of Wastewater

The physicochemical characteristics of different wastewater types and the efficacy of treatment systems primarily dictate their influence on human health and the environment. Wastewater emanates from several sources, such as residential, industrial, and agricultural operations, each introducing unique contaminants that affect environmental and health consequences. Efficient wastewater treatment is essential to alleviate these effects and guarantee adherence to international discharge, recycling, and reuse requirements.

Numerous international organizations offer directives for the management of treated and untreated wastewater, focusing on essential elements such as sludge management, emissions, and water reclamation (Bush et al., 2011). The environmental impacts of wastewater encompass the pollution of natural water bodies, eutrophication, and the introduction of toxic compounds into ecosystems. The inadequate management of wastewater adversely

impacts human health by facilitating the proliferation of waterborne infections and exposing communities to hazardous substances.

Figure 1 depicts the environmental consequences of wastewater from residential, agricultural, and industrial sources, emphasizing its effects on human health and aquatic ecosystems. As businesses develop and urban populations increase, comprehensive wastewater treatment techniques are essential for preserving public health and environmental sustainability.

4.1 Environmental Effects of Wastewater

Wastewater from different sources can harm the environment by changing the physical and chemical makeup of water systems. This can lead to negative effects on ecosystems and human health. Contaminants, including heavy metals, organic compounds, and nutrients from industrial, agricultural, and residential origins, contribute to water pollution, leading to problems such as eutrophication, reduced dissolved oxygen levels, and biological amplification (Al-Hazmi et al., 2023).

Research shows that wastewater can significantly affect both living and non-living parts of water ecosystems. This is evident through changes in pH, temperature, and clarity of the water. The bioaccumulation of harmful substances in aquatic organisms presents considerable threats to ecosystem integrity and human health. Pollutants, such as heavy metals, including Zn, Pb, and Cd, accumulate in the tissues of fish and other aquatic creatures, frequently exceeding safety standards established by health organizations. This impacts not only on individual species but also results in larger ecological ramifications, including alterations in water biodiversity and prolonged environmental deterioration.

Moreover, wastewater may function as a nitrogen supply when effectively handled, facilitating agricultural irrigation and soil enhancement (Silva, 2023). Nonetheless, its misuse presents significant concerns, such as the introduction of viruses and accelerated environmental deterioration. Persistent organic pollutants, heavy metals, and other hazardous substances in wastewater can exert enduring impacts on aquatic flora and fauna, with certain contaminants bioaccumulating over time and inducing chronic health problems in aquatic organisms.

4.2 Health Impacts of Wastewater

Wastewater functions as a significant reservoir for pathogens, such as bacteria, viruses, and protozoa, presenting considerable health hazards to humans and ecosystems alike. Medical wastewater, especially from healthcare institutions, harbors elevated levels of pathogens like *E. coli*, *Salmonella*, and hepatitis viruses, requiring stringent identification and treatment protocols. Research demonstrates that viruses in wastewater can be concentrated up to 1000 times more than in natural settings, highlighting the necessity

for efficient wastewater monitoring and treatment approaches (Dalkmann et al., 2012).

Advanced diagnostic tools like electrochemical biosensors and real-time polymerase chain reaction (RT-qPCR) are effective in detecting various infections, such as SARS-CoV-2 and some neglected tropical diseases. These illnesses can present in both acute and chronic forms, resulting in symptoms such as gastroenteritis, cardiovascular issues, and chronic ulcers. The intricate microbial diversity in wastewater hinders pathogen detection, rendering conventional culture techniques ineffective. New technologies, such as surface-enhanced Raman spectroscopy combined with machine learning, offer quick and efficient ways to identify pathogens (United Nations Environment Programme, 2021).

Regulatory frameworks underscore the imperative for personalized risk evaluations to mitigate health hazards associated with wastewater pollution. Entities like the World Health Organization (WHO) establish rules to guarantee that wastewater treatment facilities adhere to safety standards, therefore mitigating the dangers of disease outbreaks and chronic health issues.

4.3 Wastewater Treatment Techniques

The identification and treatment of pathogens in wastewater encompass several procedures, including traditional techniques like chlorination and ultraviolet disinfection. However, these methods have limitations, particularly when it comes to cysts and oocysts of protozoa, which are quite resistant to standard treatments (Tsuchihashi et al., 2002). Consequently, researchers have devised novel wastewater treatment techniques that use enhanced filtration, chemical treatments, and biological interventions to successfully limit these dangers.

4.3.1 Primary Treatment

Primary treatment is the preliminary phase in wastewater management, aimed at eliminating substantial suspended and floating particles from untreated wastewater. This phase includes mechanical operations like screening, grit removal, and sedimentation to segregate solid materials from the liquid phase. Sometimes, we use chemical additives to speed up the sedimentation process, thereby enhancing the efficiency of solid removal.

This phase significantly decreases the biochemical oxygen demand (BOD) of wastewater by around 20–30% and removes up to 50–60% of total suspended particles. While basic treatment removes large debris and bigger particles, it doesn't completely get rid of germs, dissolved pollutants, or nutrients. More treatment steps are needed (Adler et al., 2011).

4.3.2 Secondary Treatment

Secondary therapy aims to address the dissolved organic matter that persists following the first treatment. This phase predominantly depends on biological mechanisms, whereby microorganisms, such as bacteria and protozoa, metabolize organic contaminants and

transform them into water, carbon dioxide, and biomass. This process markedly improves wastewater quality by decreasing BOD by up to 85% and eliminating organic pollutants.

The secondary treatment process generally uses methods that involve oxygen to help break down waste. These methods include activated sludge, trickling filters, and biofilm reactors. Supplementary procedures, like sedimentation and disinfection, provide further diminution of microbial concentration. The sludge produced during this phase can be treated in anaerobic digesters, yielding biogas, a combination of methane and carbon dioxide, that can be used for energy generation.

Additionally, we use denitrification and nitrification procedures to reduce nitrogen pollution (Sunny et al., 2020; Alexandrino et al., 2004). Effluent after secondary treatment may still harbor microbiological, chemical, and metallic pollutants, necessitating further purification prior to safe reuse or release into natural water bodies.

4.3.3 Advanced Wastewater Treatment Technologies

Advanced wastewater treatment systems go beyond standard methods. They focus on removing tough pollutants like medicines, heavy metals, and chemicals that can disrupt hormones. These procedures are very effective in guaranteeing that treated wastewater complies with rigorous environmental and health regulations for reuse and safe release. Membrane filtration methods, like microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, are effective at removing germs, viruses, and small particles. Advanced oxidation processes (AOPs), such as ozonation, photocatalysis, and Fenton reactions, decompose organic pollutants and neutralize hazardous substances. Electrochemical treatment procedures, including electrocoagulation and electrooxidation, are used to eliminate heavy metals, organic contaminants, and infections (Kumar & Pal, 2018). Constructed wetlands offer a nature-based approach that utilizes plant and microbial interactions to effectively and sustainably eliminate toxins. Microbial fuel cells (MFCs) are a novel method that enables concurrent wastewater treatment and energy recovery, hence enhancing a sustainable and circular wastewater management system. While these modern technologies are promising, they require more optimization and investment to guarantee their extensive application and integration into traditional wastewater treatment systems.

4.3.4 Tertiary Treatment

Tertiary treatment is the last purification phase in wastewater treatment, aimed at achieving near-total elimination of remaining pollutants prior to the release or reuse of wastewater. This phase encompasses several essential processes. Disinfection techniques, including chemical procedures (such as chlorination and ozonation) and physical ones (such as UV radiation and ultrasonication), are utilized to eradicate residual infections.

Advanced biological and chemical methods are employed for nutrient removal, particularly the extraction of nitrogen and phosphorus, to mitigate eutrophication in receiving water bodies. Furthermore, activated carbon filtering is employed to eliminate micropollutants, such as pharmaceutical residues and pesticides. Desalination and water reuse methods, such as reverse osmosis and electrodialysis, transform cleansed wastewater into drinkable or industrial-grade water. Recent studies suggest that the integration of ultrasonication, UV therapy, and ozonation improves disinfection efficacy by generating free radicals, hence enhancing microbial control (Christou et al., 2024).

4.3.4 Energy Recovery from Wastewater Treatment

Current wastewater treatment facilities are progressively integrating energy recovery methods to enhance sustainability and diminish operational expenses. The anaerobic digestion of sludge generates biogas, a byproduct high in methane, which may be utilized for power generation, hence supporting the facility's total energy requirements. Moreover, cutting-edge technologies like hydrothermal carbonization and microbial fuel cells (MFCs) present promising opportunities for energy recovery. Hydrothermal carbonization converts sludge into biochar, which may be utilized as a soil amendment or as an energy source (Saguti et al., 2023). Microbial fuel cells utilize microbial metabolism to produce bioelectricity and clean wastewater, providing the twin advantages of energy generation and wastewater remediation.

4.3.5 Future Trends in Wastewater Treatment

The future of wastewater treatment will be influenced by the incorporation of smart technology and artificial intelligence (AI), enhancing treatment processes for improved efficiency and sustainability. AI-driven monitoring systems will optimize operational performance by forecasting pollutant loads, automating process modifications, and enhancing resource allocation. Concurrently, decentralized wastewater treatment systems are becoming increasingly popular, particularly in arid areas, as they provide localized treatment and reuse options. This method diminishes dependence on centralized infrastructure and improves water security (Periyasamy, 2024). Furthermore, green infrastructure, including nature-based solutions like wetlands and biofilters, is under investigation.

4.4 Innovative Solutions for Safer Wastewater Treatment and Reuse

To address growing problems like water shortages, pollution, and environmental damage, it is important to create and use new ways to improve wastewater treatment and reuse. Traditional wastewater treatment methods work but often fail to remove new pollutants like medicines, tiny plastic particles, and chemicals that can interfere with hormones. Researchers have looked into new technologies and methods to tackle this issue. They have combined improvements in nanotechnology, bioengineered filters, principles

of a circular economy, and real-time monitoring systems. These improvements improve the efficiency of wastewater treatment and facilitate sustainable resource management by encouraging the reuse of treated water in agricultural, industrial, and potable uses (Jerie et al., 2024).

The implementation of nanotechnology-based technologies is a very potential area of innovation in wastewater treatment. Nanomaterials, like graphene membranes, carbon nanotubes, and photocatalytic nanoparticles, are very good at adsorbing substances. They can effectively remove pathogens, heavy metals, and long-lasting organic pollutants. New developments in membrane bioreactor (MBR) technology use nanomaterials along with biological treatment methods. This greatly improves the breakdown of pollutants and increases energy efficiency (Khan et al., 2024). These tiny technologies improve how well pollutants are removed and lower costs and energy use, making wastewater treatment more sustainable and affordable.

A novel method in wastewater treatment encompasses bioengineered filtration and enzymatic bioremediation. Scientists have created biofilters using genetically altered bacteria that can efficiently decompose complex organic substances, medicines, and industrial pollutants. Enzymatic bioremediation uses specific enzymes to find and break down harmful chemicals into harmless products, helping to clean up wastewater pollutants. Bioengineered systems are very helpful for cleaning wastewater from drug companies and hospitals because regular treatment methods don't remove certain harmful chemicals effectively. A paradigm shift in wastewater treatment has been noted with the implementation of "circular economy" strategies, which priorities the collection and reuse of valuable materials in wastewater streams. Contemporary wastewater treatment facilities are evolving into resource recovery centers, whereby clean water, bioenergy, and reusable nutrients are retrieved from waste streams. Anaerobic digestion facilitates the transformation of organic waste into biogas, which may be used for heating and energy generation. The extraction of nutrients like nitrogen and phosphorus from wastewater enables the creation of biofertilizers, decreasing reliance on synthetic fertilizers, and mitigating agricultural runoff pollution. This comprehensive strategy coincides with international sustainability objectives by enhancing resource efficiency and reducing environmental consequences (Sunny et al., 2021b).

Additionally, real-time monitoring and smart wastewater treatment technologies are changing the industry by helping manage processes more accurately and flexibly. Combining Artificial Intelligence (AI) and Machine Learning (ML) with sensors helps wastewater treatment plants predict pollution levels, improve treatment processes, and reduce chemical usage. These intelligent technologies provide the early identification of impurities, guaranteeing that treated water consistently complies with rigorous

safety criteria. The Internet of Things (IoT) augments the capabilities of wastewater treatment facilities by enabling remote monitoring and predictive maintenance; hence, it minimizes downtime and enhances overall system dependability (Iffy et al., 2023a).

Decentralized wastewater treatment systems represent an innovative option that is increasingly gaining prominence, especially in water-scarce and isolated areas. In contrast to traditional centralized systems that require substantial infrastructure, decentralized treatment units' function locally, enabling communities, businesses, and agricultural sectors to treat and recycle water on site. Technologies such as engineered wetlands, bio electrochemical systems, and portable filters help treat wastewater effectively and affordably. This reduces the need for big treatment plants and improves water access in areas that lack it (Khan et al., 2024).

Concerns about microplastic pollution in wastewater have led to the development of advanced filtration systems that aim to remove these harmful particles before they enter natural water sources. Innovative technologies, like electro spun nanofiber membranes and magnetic separation techniques, provide effective methods for microplastic removal, thereby averting their buildup in aquatic environments and potential entry into the food chain.

Hybrid treatment systems that use different methods like ultrasonication, UV light, and ozonation are very effective at removing germs and chemical waste. These hybrid approaches utilize synergistic effects to achieve enhanced disinfection and degradation rates, guaranteeing that wastewater is both safe for release and appropriate for direct reuse in irrigation and industrial applications.

With the increasing worldwide need for water, it is essential to implement and expand these creative technologies to improve wastewater treatment and reuse. By using new technology, recycling ideas, and smart monitoring systems, wastewater treatment can change from just getting rid of waste to focusing on recovering valuable resources sustainably. Ongoing investment in research and development, along with favorable legislative frameworks, will be essential in expediting the global deployment of these technologies. Ultimately, these advances facilitate a future in which wastewater is regarded not as a liability but as a precious resource that enhances water security, environmental sustainability, and economic development (Wang et al., 2023).

4.5 Regulatory Frameworks and Public Health Guidelines

Effective wastewater treatment and reuse require strict rules and health standards to ensure safe water, protect the environment, and manage resources sustainably. Governments, international organizations, and regulatory bodies have developed extensive standards to regulate wastewater discharge, treatment quality, and reuse usage. These frameworks are essential for reducing hazards

related to waterborne illnesses, chemical pollutants, and ecosystem degradation; therefore, they protect human health and the environment.

Globally, the World Health Organization (WHO) and the United Nations Environmental Program (UNEP) have established essential requirements for wastewater treatment and reuse, prioritizing microbiological safety and reducing chemical hazards. The WHO recommendations define permissible thresholds for pathogens, heavy metals, and organic contaminants in treated wastewater, ensuring compliance with health-oriented objectives for agricultural, industrial, and potable uses. Likewise, the United Nations Sustainable Development Goal (SDG 6) emphasizes the necessity of universal access to clean water and sanitation, highlighting the importance of effective wastewater management regulations (World Health Organization, 2020).

Several countries have national environmental protection agencies that oversee wastewater treatment plants, requiring adherence to Environmental Protection Agency (EPA) standards and regional regulations like the European Union Water Framework Directive. These rules mandate that companies and municipalities implement modern treatment technologies to reduce pollutants and guarantee that treated water complies with established quality criteria prior to discharge or reuse (Sunny et al., 2021a). Moreover, rigorous monitoring and reporting systems are implemented to ensure compliance and identify new pollutants that may threaten human health and ecosystems.

The basic aspect of wastewater management is the categorization of water reuse uses, which dictates the necessary amount of treatment. In several countries, treated wastewater is classified into various categories according to its intended application. Class A recycled water undergoes extensive treatment and is appropriate for direct potable reuse, whereas Class B and C waters are designated for irrigation, industrial applications, and environmental restoration (Kuddus et al., 2022). Countries like Singapore, Israel, and Australia have initiated extensive wastewater recycling projects, showcasing the viability and safety of direct and indirect potable reuse under stringent regulatory supervision.

In addition to regulatory compliance, public health recommendations are crucial for the safe treatment of wastewater, especially in developing areas with inadequate sanitation infrastructure. The WHO Sanitation Safety Planning (SSP) Framework offers a systematic methodology for evaluating health hazards and executing control measures across various phases of wastewater treatment and reuse. The FAO's Guidelines on Safe Use of Wastewater in Agriculture safeguard farmers and consumers against pollutant exposure by promoting appropriate irrigation methods and water quality monitoring (United Nations Environment Programme, 2021).

To improve the efficacy of regulatory frameworks, integrated water governance strategies are being implemented, incorporating multi-stakeholder cooperation among governments, industry, and research institutes. Public-private partnerships (PPPs) have arisen as a viable strategy for funding wastewater infrastructure, guaranteeing long-term sustainability and adherence to environmental requirements. Digital tools, such as real-time monitoring and AI compliance tracking, are revolutionizing the enforcement of regulations. They help make decisions based on data and allow for quick reactions to pollution incidents (Ifty et al., 2024).

Notwithstanding these developments, issues persist in enforcing wastewater rules, especially in low-income areas where infrastructure and budget limitations impede compliance (Sazzad et al., 2023). To tackle these challenges, we need to improve skills, share technology, and provide financial incentives to encourage businesses and local governments to invest in better wastewater treatment systems. Enhancing regulatory supervision, encouraging community involvement, and advancing awareness campaigns are essential for achieving broad compliance with wastewater safety requirements.

Figure 2 illustrates the link between the importance of human health concerns and the detection thresholds of contemporary analytical techniques employed in wastewater surveillance. The image highlights the difficulties in detecting new pollutants at low concentrations and the necessity for enhanced analytical methods. As regulatory frameworks develop, the use of new detection technologies will be crucial for enhancing wastewater safety standards and safeguarding public health.

As wastewater treatment advances, regulatory frameworks and public health recommendations must develop to tackle new toxins, the effects of climate change, and the increasing need for water reuse. A coordinated international initiative is essential to create universal water quality standards, improve transboundary cooperation, and advance novel policy tools that facilitate sustainable wastewater management. By strengthening regulatory compliance and incorporating science-based public health policies, society may transform wastewater from a threat into a useful resource that enhances environmental resilience and water security.

4.6 Advanced public health implications in wastewater treatment and reutilization

4.6.1 Public health hazards and disease loads

Poorly handling and getting rid of wastewater poses big health risks to everyone because it lets pathogens, heavy metals, pharmaceutical contaminants, and antibiotic-resistant bacteria (ARB) get into the water supply. The World Health Organization (WHO) reports that waterborne diseases, including cholera, dysentery, typhoid, and hepatitis A, persistently impact millions worldwide, especially in areas with insufficient wastewater management systems. New

Table 1. Comparative Analysis of Traditional Water Treatment Methods and Their Efficacy in Pathogen and Pollutant Removal

Water Treatment Method	Key Pathogen or Pollutant	Effectiveness (%)	Estimated Cost (USD per 1000 gallons)	Common Use	Reference
Boiling	E. coli	70.5%	0.50	Household	(Ghaudenson et al., 2021)
Sand Filtration	suspended solids, turbidity, and certain pathogens	-	0.10	Community	(Deviprasad et al., 2023)
Chlorination	Echovirus, rotavirus and adenovirus	-	0.20	Municipal	(Saguti et al., 2023)
Flocculation	chemical oxygen demand	93.7%	0.15	Industrial	(Wang et al., 2023)
Sedimentation	-	90%	0.05	Rural	(Juraev et al., 2022)

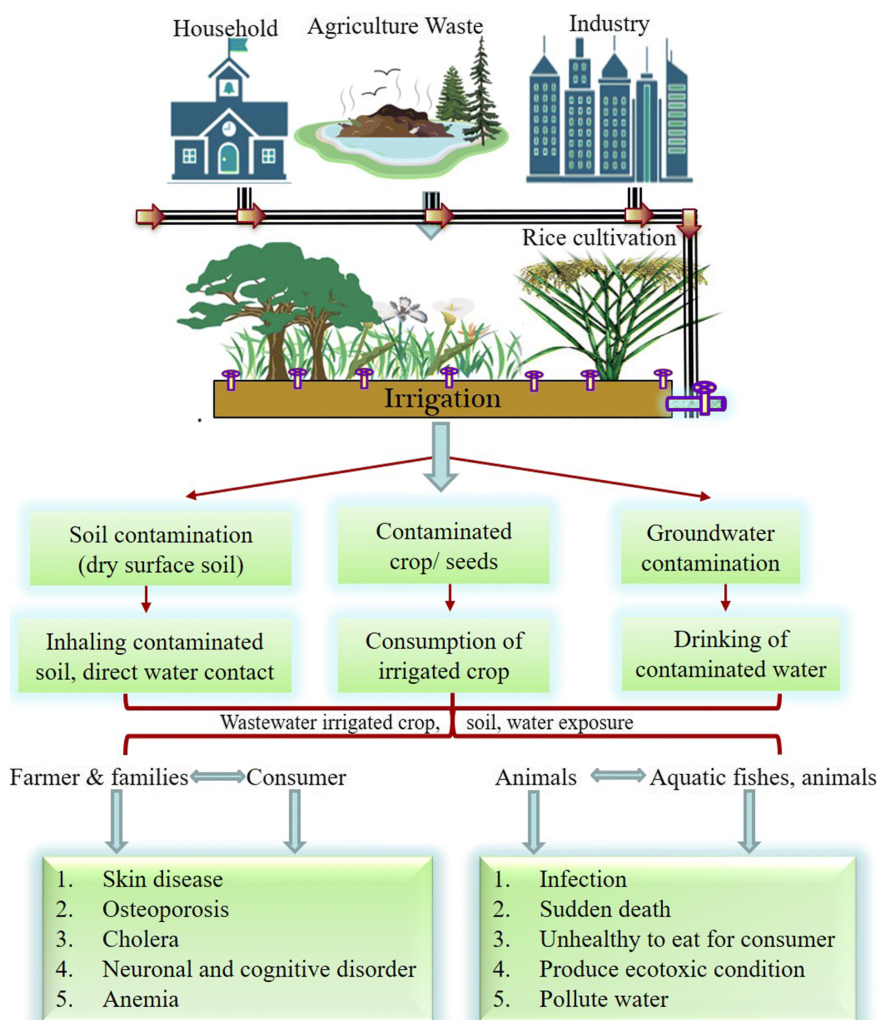


Figure 1. Diagram of Wastewater impacts from different sources.

Table 2. Industrial Pollutants and Their Environmental Impacts

Industry Type	Key Pollutants	Potential Environmental Impacts
Textile and Leather	Total solids, BOD, surfactants, dyes	Water coloration, toxicity to aquatic life, oxygen depletion
Food Industries	BOD, COD, suspended solids, micro and macro nutrients	Eutrophication, oxygen depletion, impact on aquatic biodiversity
Iron and Steel	COD, BOD, metals, cyanides, acids, ores	Toxicity to aquatic life, corrosion and sedimentation problems
Petrochemical	Oil, phenols, BOD, COD, chromium	Oil spills, toxicity, heavy metal contamination, oxygen depletion
Mining Industries	Suspended solids, metals, acids, salts	Habitat destruction, soil and water acidification, heavy metal pollution
Electronic Industries	Organic chemicals, metals and metal ores, COD	Toxicity to human and aquatic life, persistent environmental pollutants

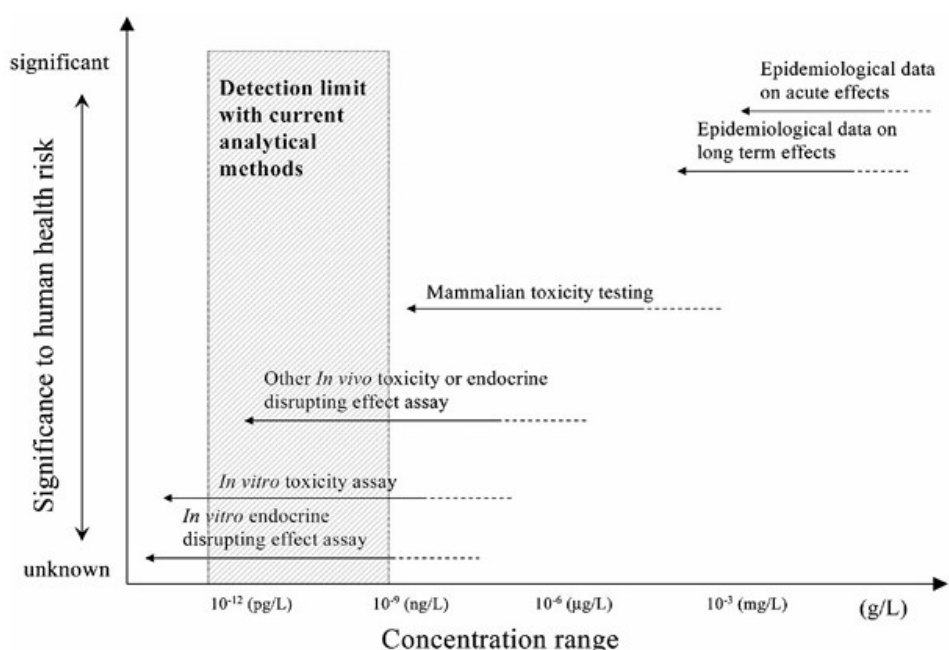


Figure 2. Conceptual framework for various assays for trace organic compounds and their relative significance to human health risk (Tsuchihashi et al., 2002)

studies show that new pollutants, like endocrine-disrupting chemicals (EDCs) and microplastics, are becoming more common. These pollutants are linked to long-term health problems like reproductive problems, metabolic problems, and possibly cancer.

4.6.2 Wastewater and Oncological Risks

Increasing scientific data indicates a direct relationship between extended exposure to improperly treated wastewater and a heightened cancer risk. Pollutants like heavy metals (like arsenic, cadmium, and chromium), heavy metals (like arsenic), and persistent organic pollutants (POPs) that are found in wastewater can cause cancer. These pollutants are linked to the development of liver, bladder, and lung cancer. Specifically, industrial effluents release high amounts of genotoxic and mutagenic substances that can damage DNA and cause tumors to start and grow. Also, pharmaceutical residues and substances that mess with hormones that are found in wastewater have been connected to hormone-related cancers like breast, ovarian, and prostate cancers. To solve this big problem, we need to use modern wastewater treatment technology that can effectively get rid of contaminants that can cause cancer and strict rules on the discharge of industrial effluent.

4.6.3 The Function of Wastewater in Antibiotic Resistance

A lot of medicines and antibiotic residues end up in wastewater, which helps antibiotic-resistant bacteria (ARBs) and antibiotic resistance genes (ARGs) grow. This is very bad for public health around the world. Because pharmaceutical chemicals aren't properly removed from wastewater treatment plants (WWTPs), they often become breeding grounds for bacteria that are resistant to antibiotics. Researchers have shown that ARGs can be passed from one microbial community to another in wastewater treatment plants. This makes it more likely that people will get diseases that are resistant to treatment. To make this worry go away, wastewater treatment systems need to include advanced oxidation processes (AOPs), bioelectrochemical treatments, and rules that keep pharmaceuticals from getting contaminated.

4.6.4 Surveillance of Wastewater for Public Health Assessment

The study of wastewater-based epidemiology (WBE) has become a useful tool for keeping an eye on public health trends and finding infectious disease outbreaks like COVID-19, polio, and norovirus early on. By looking at viral RNA, bacterial pathogens, and chemical biomarkers in wastewater, health officials can figure out how common illnesses are in a community and act quickly to stop them. Many nations are currently incorporating wastewater-based epidemiology into their national health surveillance systems to improve pandemic preparedness and response efficacy.

4.6.5 Effects of Wastewater on At-Risk Populations

Communities in low-income areas and informal settlements disproportionately suffer from the negative health effects of inadequate wastewater management. In numerous underdeveloped nations, untreated or inadequately treated sewage is released into

open water bodies, resulting in significant epidemics of waterborne infections, aggravated malnutrition, and hindered childhood development. Also, industrial waste water that contains high amounts of heavy metals like lead, arsenic, and mercury makes health problems worse by polluting drinking water, preventing brain development, and weakening the immune system. Targeted measures, such as decentralized wastewater treatment systems, enhanced sanitation infrastructure, and public health education programs, are essential to alleviate these hazards and protect vulnerable people.

4.6.6 Implications of Climate Change on Public Health

Climate change is exacerbating public health hazards associated with wastewater by increasing the occurrence of extreme weather events, such as floods and droughts, which compromise sanitation infrastructure and wastewater treatment systems. Increasing temperatures further intensify microbial proliferation, promoting the spread of watery illnesses. To lower the risks to public health in a world where the climate is changing, it is important to use climate-resilient technologies for treating wastewater, improve the way stormwater is managed, and use nature-based solutions like constructed wetlands.

4.7 Recommendations for Public Health Safeguarding

4.7.1 Improving Regulatory Frameworks

Governments and international regulatory bodies need to set strict standards for wastewater discharge, with a focus on getting rid of pollutants that cause cancer and bacteria that are resistant to antibiotics (ARBs) (Table 2).

4.7.2 Enhancing Treatment Technologies

Invest more in the research and implementation of advanced oxidation processes, membrane bioreactors, and bioengineered filtration systems to improve the effectiveness of wastewater purification.

4.7.3 We are enhancing Wastewater-Based Epidemiology

Incorporating WBE into national and international health surveillance systems to improve early disease identification and outbreak response strategies. We are enhancing public awareness by executing educational campaigns to promote safe wastewater reuse practices, mitigate pharmaceutical contamination, and elevate public participation in water safety initiatives. Emphasizing the advancement of wastewater treatment infrastructure in marginalized communities to mitigate health disparities and foster environmental justice.

5 Conclusion

This research has shown that wastewater treatment is a crucial approach for attaining environmental and economic sustainability. The research substantiates the significance of wastewater treatment in four principal domains: transforming waste into potable water, producing renewable energy, mitigating environmental

contamination, and promoting sustainable urban growth. Through the extraction of pollutants, neutralization of dangerous compounds, and eradication of pathogens, wastewater treatment safeguards public health and guarantees a cleaner, more sustainable water supply. Moreover, wastewater treatment facilitates resource recovery, since treated effluent may be utilized for agricultural irrigation, industrial applications, and, in certain sophisticated systems, even for potable reuse. The transformation of organic waste into biogas and the recovery of vital nutrients enhance the economic feasibility of wastewater treatment, in accordance with circular economic principles. Nonetheless, obstacles such as elevated operational expenses, energy-demanding procedures, and infrastructural constraints persist in obstructing extensive adoption, especially in developing areas. Addressing these obstacles necessitates inventive technical advancements, strong regulatory structures, and augmented investment in wastewater infrastructure. Furthermore, public awareness and community involvement are essential in promoting the adoption of treated wastewater reuse. With the increasing worldwide demand for water, wastewater treatment should be acknowledged not just as an environmental liability but as an essential solution for water security, climate resilience, and sustainable development. The amalgamation of advanced technology, policy endorsement, and cooperative governance will be pivotal in evolving wastewater management into a fundamental catalyst for sustainability in the forthcoming decades.

Author contributions

M.S.A., M.J.I., M.R.J., and F.N. contributed to the conceptualization, fieldwork, data analysis, original draft writing, editing, funding acquisition, and review of the study. M.S.A., M.N.H., M.H., R.H., and M.A. were responsible for research design, methodology validation, analysis, visualization, reviewing, and editing. A.C. and F.M.K. participated in conceptualization, investigation, visualization, reviewing, editing, and proof-reading. A.R.S. played a key role in conceptualization, methodology validation, analysis, investigation, reviewing, funding acquisition, supervision, and editing. All authors have read and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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