PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 28 (5) 1553-1572 May 2024

An Overview of Wastewater Characteristics, Treatment and Disposal: A Review

[1]ETSUYANKPA, MB; [1]AUGUSTINE, AU; [1]MUSA, ST; [2]MATHEW, JT; [2]ISMAIL, H;
[3]SALIHU, AM; [2]MAMMAN, A

[1]*Department of Chemistry, Federal University of Lafia, Nasarawa State, Nigeria*
[2]*Department of Chemistry, Ibrahim Badamasi Babangida University Lapai, Niger State, Nigeria*
[3]*Department of Chemistry, Federal University of Technology Minna, Nigeria*

Corresponding Author Email: johntsadom@gmail.com; jmathew@ibbu.edu.ng
**ORCID: https://orcid.org/0000-0001-9514-5330*
**Tel: +2347036068583*

Co-Authors Email: myankpa@yahoo.com; safftankomusa@gmail.com; a.salihu@futminna.edu.ng; ismailah@ibbu.edu.ng; dmamman51@yahoo.com

ABSTRACT: Wastewater treatment is a critical aspect of environmental management, aimed at mitigating the adverse effects of urbanization and industrialization on water bodies. This review provides a comprehensive overview of wastewater characteristics, treatment methods, and disposal options by harvesting data from secondary sources. Data obtained reveals that various treatment processes are employed to remove or reduce contaminants from wastewater, including physical, chemical, and biological methods. This review underscores the importance of wastewater treatment in safeguarding water resources and public health, while also emphasizing the importance of considering the broader environmental implications of treatment and disposal practices.

DOI: https://dx.doi.org/10.4314/jasem.v28i5.28

Cite this Article as: ETSUYANKPA, M. B; AUGUSTINE, A. U; MUSA, S. T; MATHEW, J. T; ISMAIL, H; SALIHU, A. M; MAMMAN, A (2024). . An Overview of Wastewater Characteristics, Treatment and Disposal: A Review. *J. Appl. Sci. Environ. Manage.* 28 (5) 1553-1572

Dates: Received: 21 February 2024; Revised: 22 March 2024; Accepted: 20 April 2024 Published: 20 May 2024

Keywords: Characteristics; Disposal; Environmental; Reuse; Treatment; Wastewater

Wastewater management is vital for environmental sustainability and public health amid rapid urbanization and industrial growth. The escalating production of wastewater demands effective strategies for water resource preservation and pollution control. This review offers a thorough analysis of wastewater attributes, treatment techniques, and disposal options, emphasizing the importance of holistic management strategies. By understanding wastewater characteristics and implementing appropriate treatment and disposal methods, we can mitigate environmental degradation, safeguard public health, and ensure the sustainable use of water resources in the face of increasing urbanization and industrial activities (Silva, 2023).

Wastewater originates from diverse origins, encompassing domestic, industrial, and agricultural sectors. Domestic wastewater, commonly referred to as sewage, emanates from residential dwellings, commercial establishments, and institutional facilities. It contains a myriad of contaminants, including organic matter, nutrients (such as nitrogen and phosphorus), pathogens, and suspended solids. Industrial wastewater, derived from manufacturing plants, mining operations, and other industrial processes, often contains elevated concentrations of specific pollutants, such as heavy metals, organic chemicals, and hazardous substances. Additionally, agricultural runoff, comprising irrigation runoff and

Corresponding Author Email: **johntsadom@gmail.com; jmathew@ibbu.edu.ng*
**ORCID: https://orcid.org/0000-0001-9514-5330*
**Tel: +2347036068583*

animal waste, introduces nutrients, pesticides, and sediments into water bodies (Koul *et al*., 2022).

The composition of wastewater exhibits variability based on its source, geographic location, and prevalent land use practices. Urban locales typically yield wastewater with heightened organic and nutrient content due to concentrated human activities, while industrial areas may produce wastewater laden with industry-specific pollutants. A thorough comprehension of wastewater characteristics is imperative for devising tailored treatment strategies and selecting appropriate disposal methodologies (Capodaglio, 2023).

This review aims to provide a comprehensive grasp of the complex challenges in wastewater management, targeting stakeholders, practitioners, and researchers involved in water resource conservation and environmental stewardship. Effective wastewater management is pivotal for sustainably utilizing water resources, bolstering ecosystem health, and ensuring public health and welfare. By comprehensively addressing the multifaceted aspects of wastewater management, this review seeks to equip decision-makers with the knowledge needed to implement informed policies and practices that safeguard both environmental sustainability and public well-being (Al-Addous *et al*., 2023).

Wastewater Characteristics: This table 1 below, provides a snapshot of some key constituents found in wastewater, their descriptions, common sources, and potential impacts on the environment and public health.

Table 1: Outlining wastewater characteristics

Pollutant/ Contaminant	**Description**	**Sources**	**Potential Impacts**	**Treatment Methods**	**References**
Organic Matter	Decomposable materials like food waste and fecal matter	Domestic wastewater, industrial effluents	Oxygen depletion, foul odor	Biological treatment, chemical oxidation	Olorunsola *et al*., 2024
Nutrients	Nitrogen, phosphorus, potassium compounds	Domestic, agricultural runoff	Eutrophication, algal blooms	Biological nutrient removal, chemical precipitation	Mathew *et al*., 2024c
Heavy Metals	Lead, mercury, cadmium, chromium, arsenic	Industrial discharges, urban runoff	Toxicity, bioaccumulation	Precipitation, filtration, ion exchange	Mathew *et al*., 2023a
Pathogens	Bacteria, viruses, parasites	Sewage, animal waste	Waterborne diseases	Disinfection (chlorination, UV treatment)	Adetunji *et al*., 2024a
Suspended Solids	Soil, sediment, organic matter, debris	Urban runoff, erosion, industrial processes	Habitat degradation, reduced water quality	Sedimentation, filtration, settling ponds	Inobeme *et al*., 2023a

Sources of Wastewater: Wastewater emanates from diverse sources, each imparting unique characteristics and pollutants. A comprehensive comprehension of these sources is imperative for efficient wastewater management. Domestic sources, such as residential households and commercial establishments, produce sewage laden with organic matter, nutrients, and pathogens. Industrial activities contribute industrial wastewater containing heavy metals, toxic chemicals, and suspended solids. Agricultural practices yield agricultural wastewater, rich in nutrients, pesticides, and sediment. Stormwater runoff, derived from urban and industrial areas, carries contaminants like sediment, oil, grease, and bacteria. Combined sewer systems exacerbate wastewater issues in older urban regions, leading to combined sewer overflows during heavy rainfall events. Recognizing the origins and constituents of wastewater aids in tailoring appropriate treatment and disposal strategies to mitigate environmental pollution and safeguard public health (Silva, 2023). The primary sources of wastewater include:

Domestic Sources: Domestic wastewater, commonly referred to as sewage, originates from residential households, commercial establishments, and institutional facilities. It includes wastewater from various sources such as toilets, sinks, showers, laundry, and kitchen activities. This wastewater contains a mixture of organic matter, nutrients like nitrogen and phosphorus, pathogens such as bacteria and viruses, and household chemicals. In urban areas, domestic wastewater constitutes a substantial proportion of total wastewater generation due to dense populations and high water consumption rates. Managing domestic wastewater is essential to prevent contamination of water bodies, mitigate public health risks, and ensure the proper treatment and disposal of sewage to protect both human health and the environment (Koul *et al*., 2022). Industrial Sources: Industrial wastewater originates from manufacturing processes, industrial activities, and commercial enterprises, encompassing discharges from factories, refineries, power plants, and chemical processing plants. This wastewater can harbor diverse pollutants specific to each industry, including heavy metals, toxic chemicals, organic solvents, and suspended solids. Given its complex composition, treating industrial wastewater often necessitates specialized processes tailored to remove or neutralize these contaminants effectively. Techniques such as chemical precipitation, biological treatment, and advanced oxidation are commonly employed for industrial wastewater treatment. Proper management and treatment of industrial wastewater are crucial to prevent environmental pollution and protect water resources. By implementing appropriate treatment measures, industries can minimize their environmental footprint and ensure compliance with regulatory standards for wastewater discharge or reuse (Aziz *et al*., 2023).

Agricultural Sources: Agricultural wastewater stems from farming activities like irrigation, livestock operations, and crop processing. It comprises runoff from fields treated with fertilizers and pesticides, along with animal waste from farms and feedlots. This wastewater often contains elevated levels of nutrients, pesticides, pathogens, and sediment. Managing agricultural runoff is critical to prevent water body contamination and safeguard downstream ecosystems. Strategies such as vegetative buffers, conservation tillage, and precision farming can mitigate runoff by reducing soil erosion and nutrient leaching. Implementing best management practices in agriculture helps maintain water quality, preserve aquatic habitats, and sustain biodiversity in surrounding ecosystems. Effective management of agricultural wastewater is vital for promoting sustainable farming practices and ensuring the long-term health of aquatic environments (Mathew *et al*., 2024b).

Stormwater Runoff: Stormwater runoff is the flow of precipitation over impervious surfaces like roads, parking lots, and rooftops, collecting pollutants before entering water bodies or municipal drainage systems. This runoff can contain sediment, oil, grease, heavy metals, and bacteria, gathered from urban and industrial areas. Managing stormwater runoff is essential for preventing water pollution and mitigating the impact of urbanization on aquatic ecosystems. By implementing measures such as green infrastructure, detention ponds, and permeable pavements, communities can reduce the volume and improve the quality of stormwater runoff, safeguarding water resources and protecting the health of aquatic ecosystems. Proper management of stormwater runoff is crucial for maintaining water quality, supporting biodiversity, and preserving the ecological balance in urban environments (Godyń *et al*., 2022).

Combined Sewer Overflows (CSOs): Combined sewer systems, prevalent in older urban areas, manage sewage and stormwater runoff together. However, during intense rainfall or snowmelt, the sewer system's capacity is exceeded, causing combined sewer overflows (CSOs). These events result in untreated wastewater, comprising sewage and stormwater, being discharged directly into water bodies. CSOs pose substantial environmental and public health hazards by contaminating waterways with pathogens, pollutants, and debris. This can lead to waterborne illnesses, ecological degradation, and harm to aquatic habitats. Managing CSOs is crucial to mitigate these risks and protect the health of communities and ecosystems in urban areas with combined sewer systems (Muttil *et al*., 2023).

Commercial and Institutional Sources: Commercial establishments, such as restaurants, hotels, and shopping centers, as well as institutional facilities, such as schools, hospitals, and prisons, generate wastewater from their operations and activities. This wastewater may contain similar contaminants as domestic wastewater but can also include additional pollutants specific to commercial and institutional activities, such as food waste, cleaning chemicals, and pharmaceuticals. Overall, managing wastewater from diverse sources requires integrated approaches that consider the unique characteristics and challenges associated with each source. Implementing effective wastewater management practices is essential to protect water quality, safeguard public health, and preserve ecosystems (Inobeme *et al*., 2023b).

Composition of Wastewater: The composition of wastewater can vary significantly depending on its source, geographical location, and surrounding land use practices. However, wastewater typically consists of a complex mixture of organic and inorganic substances, including but not limited to:

Organic Matter: Organic matter in wastewater originates from various sources such as human waste, food scraps, detergents, and other household products. These organic compounds include proteins, carbohydrates, fats, and oils. Organic matter contributes to the biochemical oxygen demand (BOD) of wastewater, which measures the amount of oxygen required by microorganisms to decompose organic material. High levels of organic matter can deplete oxygen levels in receiving water bodies, leading to oxygen deficiency and adversely affecting aquatic life (Koul *et al*., 2022).

Nutrients: Wastewater contains nutrients essential for plant growth, including nitrogen, phosphorus, and potassium. These nutrients come from human waste, detergents, fertilizers, and other sources. While nutrients are necessary for biological processes, excessive levels can lead to eutrophication, a process in which excessive nutrient concentrations stimulate algal growth, leading to oxygen depletion and ecological imbalances in aquatic ecosystems (Witek-Krowiak *et al*., 2022).

Suspended Solids: Suspended solids in wastewater consist of particles suspended in the water column, including soil, sediment, organic matter, and other debris. These solids can originate from erosion, runoff, industrial processes, and domestic activities. Suspended solids can impair water clarity, hinder light penetration, and smother aquatic habitats, affecting aquatic organisms and ecosystem health (Akhtar *et al*., 2021).

Pathogens: Wastewater contains a variety of pathogenic microorganisms, including bacteria, viruses, and parasites, originating from human and animal waste. Pathogens in wastewater pose significant public health risks, as they can cause waterborne diseases such as cholera, typhoid, dysentery, and gastroenteritis. Proper treatment of wastewater is essential to remove or inactivate pathogens before discharge or reuse to protect public health (Inobeme *et al*., 2023c).

Heavy Metals: Industrial wastewater may contain heavy metals such as lead, mercury, cadmium, chromium, and arsenic, originating from various industrial processes, mining activities, and urban runoff. These metals are toxic to aquatic organisms and can bioaccumulate in the food chain, posing risks to human health and ecosystem integrity. Proper management and treatment of industrial wastewater are essential to remove or reduce heavy metal concentrations to safe levels (Zhang *et al*., 2023).

Organic Chemicals: Wastewater from industrial sources may contain a wide range of organic chemicals, including solvents, pesticides, herbicides, pharmaceuticals, and industrial by-products. These chemicals can be toxic, persistent, and bioaccumulative, posing risks to aquatic organisms and human health. Advanced treatment technologies such as activated carbon adsorption, advanced oxidation processes, and membrane filtration are often required to remove organic chemicals from wastewater effectively (Aziz *et al*., 2023).

pH and Acidity: The pH of wastewater can vary depending on its source and composition. Domestic wastewater typically has a neutral to slightly alkaline pH, while industrial wastewater may have acidic or alkaline pH levels depending on the industrial processes involved. Fluctuations in pH can affect the solubility and toxicity of pollutants, as well as the effectiveness of treatment processes. Proper pH control is essential to ensure the efficiency of wastewater treatment and minimize environmental impacts (Kokina *et al*., 2022).

Temperature: Wastewater temperature can fluctuate depending on ambient conditions and the sources of wastewater. Industrial discharges may introduce heated wastewater into receiving water bodies, affecting aquatic ecosystems and thermal pollution. Temperature influences biological processes, chemical reactions, and the behavior of pollutants in wastewater, highlighting the importance of monitoring and managing wastewater temperature to protect water quality and ecosystem health (Mathew *et al*., 2023b).

In addition, wastewater is a complex mixture of organic and inorganic substances derived from various sources such as domestic, industrial, agricultural, and urban activities. Understanding the composition of wastewater is essential for designing effective treatment processes and implementing appropriate management strategies to protect water resources, safeguard public health, and preserve ecosystem integrity (Al-Hamedi *et al*., 2023).

Pollutants and Contaminants: Pollutants and contaminants are substances that, in excessive amounts, harm the environment and living organisms. They stem from diverse sources like industrial processes, transportation, agriculture, and natural phenomena. Recognizing various types of pollutants, including air, water, soil, noise, and light pollution, along with contaminants like heavy metals, pesticides, and chemicals, is pivotal. Their detrimental effects range from air and water pollution, soil degradation, to disruptions in ecosystems and biodiversity. Adverse health impacts such as respiratory diseases, cancer, and neurological disorders can result from exposure to pollutants. Mitigation strategies involve regulatory measures, technological innovations, public awareness campaigns, and international cooperation. Implementing emission controls, waste management protocols, and sustainable practices are crucial steps. By comprehensively understanding and addressing the sources and impacts of pollutants and contaminants, we can safeguard ecosystems, protect human health, and foster a sustainable environment for future generations (Münzel *et al*., 2023).

Types of Pollutants and Contaminants: Air Pollutants: Air pollutants encompass a variety of substances, including gases like carbon monoxide (CO), sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), and other pollutants. These emissions originate from diverse sources such as vehicle exhaust, industrial activities, and the combustion of fossil fuels. Carbon monoxide, primarily emitted from vehicle exhaust and industrial processes, can lead to cardiovascular problems and impair cognitive function. Sulfur dioxide, mainly released from burning fossil fuels, contributes to acid rain formation and respiratory issues. Nitrogen oxides, produced by combustion engines and industrial combustion processes, contribute to smog formation and respiratory diseases. Particulate matter, a complex mixture of solid and liquid particles, can penetrate deep into the lungs and cause respiratory and cardiovascular problems. VOCs, released from industrial processes, vehicle emissions, and solvents, are precursors to ground-level ozone formation and can cause respiratory irritation and other health issues. Effective measures to reduce these emissions are essential for improving air quality and protecting public health (Kalair *et al*., 2021).

Water Pollutants: Water contaminants comprise a diverse range of substances, including heavy metals such as mercury, lead, and cadmium, pesticides, fertilizers, pharmaceuticals, industrial chemicals, and microbial pathogens. These pollutants enter water bodies through multiple pathways, including runoff from agricultural fields, urban areas, and industrial sites, as well as direct discharge from wastewater treatment plants and improper waste disposal practices. Once in the water, these contaminants can persist for long periods, posing risks to aquatic ecosystems, wildlife, and human health. Heavy metals and chemicals can accumulate in organisms, biomagnifying through the food chain, while microbial pathogens can cause waterborne diseases and outbreaks. Effective management strategies, such as improved wastewater treatment, pollution prevention measures, and regulation of pollutant discharge, are crucial for mitigating water contamination and ensuring the safety and sustainability of water resources for present and future generations (Rashid *et al*., 2023).

Soil Contaminants: Soil pollution arises from the accumulation of toxic chemicals, heavy metals, pesticides, and other pollutants in the soil. Industrial activities, such as manufacturing and mining, release contaminants into the environment through emissions, spills, and improper waste disposal. Similarly, agricultural practices involving the use of fertilizers, pesticides, and herbicides contribute to soil contamination through runoff and leaching. Over time, these pollutants can degrade soil quality, impairing its fertility and productivity. Moreover, soil pollution poses risks to human health and ecosystems as contaminants can enter the food chain through plants and animals, potentially causing adverse health effects and disrupting ecological balance. Addressing soil pollution requires implementing pollution control measures, promoting sustainable land management practices, and remediation techniques to restore contaminated soils and safeguard human health and environmental integrity (Priya *et al*., 2023).

Noise Pollution: Noise pollution encompasses excessive or disruptive sounds generated by various sources, including transportation, industrial activities, construction, and urban areas. Prolonged exposure to high noise levels can have detrimental effects on human health, leading to hearing loss, sleep disturbances, elevated stress levels, hypertension, and cardiovascular diseases. Additionally, noise pollution can disrupt wildlife habitats and behaviors, affecting feeding, communication, and reproduction patterns in animals. In urban areas, constant exposure to noise can degrade the quality of life, impair cognitive functions, and decrease productivity. To mitigate noise pollution, measures such as sound insulation, urban planning strategies, noise barriers, and regulations on noise levels are essential. Promoting awareness about the impacts of noise pollution and adopting sound management practices can help minimize its adverse effects on both human well-being and ecological balance (Arcangeli *et al*., 2023).

Light Pollution: Light pollution arises from the overuse or mismanagement of artificial lighting, impacting natural ecosystems, wildlife behavior, and human well-being. It disrupts the natural light-dark cycle essential for the functioning of ecosystems and wildlife behaviors such as migration, feeding, and reproduction. Additionally, excessive artificial light alters the behavior and habitats of nocturnal species, leading to population declines and ecological imbalances. Moreover, light pollution contributes to energy waste, as a significant portion of emitted light is dispersed inefficiently into the atmosphere rather than illuminating intended areas. This inefficiency not only wastes energy resources but also increases greenhouse gas emissions associated with electricity generation. Addressing light pollution requires implementing lighting regulations, utilizing energy-efficient lighting technologies, and promoting responsible lighting practices to minimize its adverse impacts on biodiversity, ecosystems, and human health (Liu *et al*., 2023).

Sources of Pollutants and Contaminants: Pollutants and contaminants originate from various sources, including industrial activities like manufacturing, mining, and power generation, emitting chemicals, heavy metals, and particulate matter. Agricultural practices such as pesticide and fertilizer use contribute to water and air pollution. Transportation sources, notably vehicles and aircraft, release pollutants like nitrogen oxides and carbon monoxide. Residential activities like burning fossil fuels for heating and cooking produce pollutants such as sulfur dioxide and volatile organic compounds. Improper waste disposal, including landfill leachate and incineration emissions, also introduces contaminants into the environment. Natural events like volcanic eruptions and wildfires can also release pollutants (Figure 1).

Industrial Activities: Factories, power plants, refineries, and manufacturing facilities are major sources of pollution, releasing a wide range of pollutants into the environment through emissions, effluents, and waste disposal. In the air, these facilities emit gases such as sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM), contributing to air pollution and respiratory problems in nearby communities. In water bodies, industrial activities discharge effluents containing heavy metals, toxic chemicals, and other pollutants, contaminating surface water and posing risks to aquatic ecosystems and human health. Moreover, improper waste disposal practices, such as landfilling and incineration, can lead to soil contamination, groundwater pollution, and habitat destruction, further exacerbating environmental degradation. To address these issues, governments enforce regulations and standards to control industrial emissions and waste management practices, while industries are increasingly adopting cleaner technologies and implementing pollution prevention measures to minimize their environmental footprint and protect public health and natural resources (Badawi *et al*., 2023).

Transportation: Various modes of transportation, including vehicles, ships, airplanes, and trains, are significant contributors to air pollution, emitting pollutants such as carbon dioxide (CO2), nitrogen oxides (NOx), sulfur dioxide (SO2), and particulate matter (PM). Internal combustion engines in automobiles and trucks burn fossil fuels, releasing CO2 and NOx, which contribute to climate change and smog formation, respectively. Similarly, ships and airplanes burn heavy fuels, emitting sulfur dioxide and PM, which degrade air quality and pose health risks to nearby populations. These emissions not only impact urban areas but also affect regional and global air quality. Additionally, transportation-related pollutants can deposit onto land and water bodies, leading to soil and water contamination. To mitigate transportation-related pollution, governments and industries are increasingly adopting measures such as fuel efficiency standards, emission regulations, alternative fuels, and public transportation systems to reduce emissions and promote sustainable transportation practices. Such efforts are crucial for protecting human health and the environment while ensuring efficient mobility in modern societies (Manisalidis *et al*., 2020).

Agricultural Practices: The widespread use of fertilizers, pesticides, and herbicides in agriculture presents significant environmental and health risks. When applied excessively or inappropriately, these chemicals can leach into the soil and contaminate groundwater, affecting water quality and posing risks to aquatic ecosystems and human health. Additionally, rainfall and irrigation can cause runoff, carrying agricultural chemicals into nearby water bodies, further exacerbating pollution and harming aquatic life. Moreover, the accumulation of pesticides and herbicides in soil can disrupt soil microbial communities and degrade soil quality over time, affecting plant growth and agricultural productivity. Exposure to these chemicals has been linked to various adverse health effects in humans, including neurological disorders, reproductive issues, and certain types of cancer. To mitigate these risks, sustainable agricultural practices such as integrated pest management, organic farming, and precision agriculture techniques should be promoted to reduce reliance on chemical inputs and minimize environmental contamination while ensuring food security and safety (Onyando *et al*., 2023).

Waste Disposal: Improper disposal of solid waste, hazardous waste, and sewage poses significant risks to public health and the environment. When solid waste is inadequately managed, it accumulates in landfills, potentially leaching harmful substances into the soil and groundwater. Hazardous waste, if not properly treated and disposed of, can contaminate soil, water bodies, and air, posing serious health threats to humans and wildlife. Similarly, untreated sewage discharged into water bodies introduces pathogens and pollutants, compromising water quality and increasing the risk of waterborne diseases. Moreover, the accumulation of waste in landfills contributes to greenhouse gas emissions, exacerbating climate change. Addressing these challenges requires comprehensive waste management strategies, including proper collection, treatment, recycling, and disposal practices. Public education and awareness campaigns are also essential to promote responsible waste disposal behaviors and reduce environmental pollution, safeguarding human health and ecological integrity (Inobeme *et al*., 2023d).

Natural Processes: Natural events such as volcanic eruptions, wildfires, and dust storms release significant amounts of pollutants and contaminants into the atmosphere, impacting air and soil quality on a regional scale. Volcanic eruptions emit gases like sulfur dioxide, ash, and particulate matter, which can lead to air pollution and acid rain formation. Wildfires release smoke, ash, and carbon monoxide, contributing to air pollution and affecting respiratory health. Dust storms transport dust particles and pollutants over large distances, causing soil erosion, reducing visibility, and exacerbating respiratory problems. While these events are natural phenomena, human activities can exacerbate their impacts, such as land use changes increasing wildfire frequency and intensity. Understanding and managing the effects of these natural events are crucial for protecting human health, ecosystems, and agricultural productivity in affected regions. Effective emergency response plans and sustainable land management practices can help mitigate their adverse consequences (Akhtar *et al*., 2021).

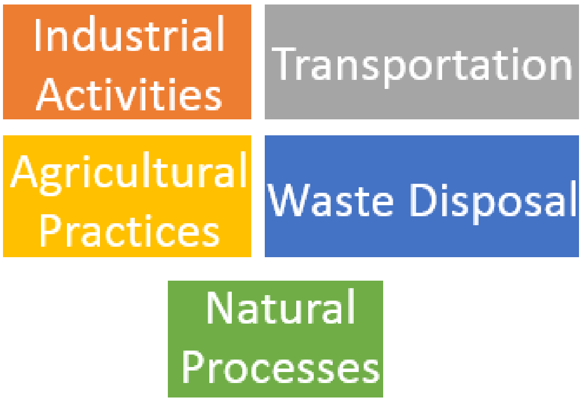

Fig 1: Sources of Pollutants and Contaminants

Effects of Pollutants and Contaminants: Environmental Impact: Pollutants pose multifaceted threats to the environment, degrading air quality by emitting harmful gases and particulate matter, leading to respiratory issues and smog formation. In water bodies, pollutants like heavy metals and chemicals disrupt ecosystems, impairing water quality and endangering aquatic life. Soil contamination from pollutants reduces fertility, affects crop productivity, and can pose health risks through food chain contamination. Moreover, pollutants contribute to climate change by releasing greenhouse gases, ozone depletion through substances like chlorofluorocarbons (CFCs), and acid rain formation from sulfur and nitrogen emissions. These environmental disruptions have far-reaching consequences, including altered weather patterns, loss of biodiversity, and ecosystem imbalance. Mitigating pollution requires concerted efforts to reduce emissions, improve waste management, and promote sustainable practices to safeguard environmental health and preserve ecosystems for future generations (Zhang *et al*., 2023). Human Health: Exposure to pollutants and contaminants poses significant health risks, including respiratory diseases like asthma and chronic obstructive pulmonary disease (COPD), cardiovascular problems such as heart attacks and strokes, neurological disorders like cognitive impairment and developmental delays, and various types of cancer. Additionally, pollutants can contribute to reproductive issues, including infertility and birth defects. Vulnerable populations, such as children whose developing bodies are more susceptible, the elderly with weakened immune systems, and individuals with pre-existing health conditions, face heightened risks of adverse health effects from pollution exposure. Protecting these vulnerable groups requires targeted interventions, stricter regulations, and public health initiatives aimed at reducing pollution levels and minimizing exposure to harmful contaminants, thereby safeguarding public health and well-being (Manisalidis *et al*., 2020). Economic Consequences: Pollution-related health issues, environmental degradation, and cleanup endeavors exact substantial economic tolls on society. Healthcare expenses escalate due to the treatment of pollution-induced illnesses like respiratory diseases and cancers. Productivity losses occur as a result of absenteeism, reduced workforce efficiency, and impaired cognitive abilities due to pollution-related health conditions. Property damage arises from pollution incidents such as oil spills, chemical leaks, and industrial accidents, requiring costly cleanup and restoration efforts. Moreover, environmental degradation diminishes ecosystem services like water purification, soil fertility, and climate regulation, leading to economic losses in agriculture, tourism, and other sectors. Altogether, these economic burdens underscore the importance of pollution prevention and mitigation strategies, highlighting the need for proactive measures to safeguard public health, preserve the environment, and ensure sustainable socio-economic development (Allioui, and Mourdi, 2023).

Mitigation and Prevention Strategies: Regulatory Measures: Governments play a critical role in controlling pollution and promoting sustainable development through regulations, standards, and policies. They establish emissions limits to restrict the amount of pollutants released into the environment, while pollution permits allocate allowable emissions levels to industries. Environmental impact assessments evaluate the potential effects of projects on the environment, informing decision-making processes to minimize negative impacts. Enforcement mechanisms ensure compliance with regulations and impose penalties for violations, fostering accountability and deterrence. Additionally, governments implement waste management policies to reduce, reuse, and recycle waste, minimizing environmental pollution and conserving resources. By enacting these measures, governments aim to protect public health, preserve natural ecosystems, and promote a harmonious balance between economic development and environmental conservation (Figure 2) (Zhu *et al*., 2021).

Technological Solutions: Advancements in pollution control technologies play a vital role in reducing emissions and mitigating environmental contamination. Scrubbers, catalytic converters, and filtration systems are instrumental in removing harmful pollutants from industrial exhaust gases, thereby improving air quality. Wastewater treatment plants employ various processes to remove pollutants and contaminants from wastewater before it is discharged into water bodies, safeguarding water quality and aquatic ecosystems. Additionally, innovations in monitoring and detection technologies enable early identification of pollution sources and prompt intervention measures. Continuous research and development efforts aim to enhance the efficiency and effectiveness of pollution control technologies, making them more affordable and accessible for industries and communities worldwide. By leveraging these technological solutions, we can combat pollution and work towards building a cleaner, healthier environment for current and future generations (Shen, and Zhang, 2024). Public Awareness and Education: Raising awareness about the detrimental impacts of pollution on human health and the environment is crucial for inspiring individuals, businesses, and communities to embrace environmentally friendly behaviors. Educating people about the importance of sustainable practices encourages them to make informed choices and take proactive steps to minimize their environmental footprint. By promoting actions such as reducing energy consumption, conserving water, practicing waste reduction and recycling, and supporting green transportation options, awareness campaigns empower individuals to contribute positively to environmental conservation efforts. Likewise, businesses can implement eco-friendly policies, invest in sustainable technologies, and adopt green supply chain practices to reduce their environmental impact. Community engagement initiatives further reinforce collective responsibility and encourage collaboration towards achieving shared sustainability goals. Together, these efforts create a culture of environmental stewardship and foster a more sustainable and resilient future for our planet (Kumar *et al*., 2021). Green Initiatives: Transitioning to renewable energy sources, such as solar, wind, and hydroelectric power, reduces greenhouse gas emissions and lessens dependence on fossil fuels, thus mitigating air pollution and combating climate change. Promoting energy efficiency through technologies and policies lowers energy consumption and reduces environmental impacts. Implementing green infrastructure, such as green roofs and permeable pavements, helps manage stormwater, mitigate urban heat island effects, and enhance biodiversity. Adopting eco-friendly practices in agriculture, such as organic farming and precision agriculture, minimizes chemical inputs, reduces soil and water contamination, and preserves ecosystems. Similarly, eco-friendly practices in industry, such as recycling, resource efficiency, and pollution prevention measures, contribute to sustainable production and minimize environmental harm. By embracing these approaches, we can protect ecosystems, safeguard natural resources, and create a healthier and more sustainable future for all (Nwokolo *et al*., 2023). International Cooperation: Collaboration among nations, organizations, and stakeholders is vital for tackling transboundary pollution and achieving global sustainability goals. International agreements like the Paris Agreement and the Montreal Protocol provide frameworks for collective action on climate change and ozone depletion, respectively. By sharing knowledge, resources, and best practices, countries can address common environmental challenges effectively. Moreover, fostering partnerships between governments, NGOs, businesses, and communities promotes innovation and facilitates the adoption of sustainable practices worldwide. Through coordinated efforts and mutual cooperation, we can safeguard the environment, mitigate pollution, and promote equitable and sustainable development for present and future generations. Generally, pollutants and contaminants pose significant challenges to environmental quality, human health, and socioeconomic well-being. By understanding their sources, effects, and mitigation strategies, society can work towards minimizing pollution, protecting ecosystems, and promoting a sustainable future (Epelle *et al*., 2023)

Fig 2: Mitigation and Prevention Strategies

Wastewater Treatment Methods: Wastewater treatment involves several methods to remove contaminants before discharge or reuse. Primary treatment involves physical processes like screening and sedimentation to remove large solids. Secondary treatment utilizes biological processes like activated sludge or trickling filters to break down organic matter. Tertiary treatment employs advanced processes such as filtration, chemical precipitation, and UV disinfection to further purify water. Advanced treatment methods like membrane filtration and reverse osmosis are used for highly contaminated wastewater or to produce high-quality effluent for specific purposes like drinking water reuse. Each method plays a crucial role in ensuring wastewater is treated effectively, protecting public health and the environment (Adetunji *et al*., 2024b) (Table 2).

Table 2: Outlining various wastewater treatment methods along with brief descriptions of each

Treatment Method	Description	Advantages	Disadvantages	Example Applications	References
Primary Treatment	Physical separation of solids and liquids through sedimentation and filtration processes.	Removes large solids and reduces BOD.	Does not eliminate dissolved pollutants.	Municipal wastewater treatment.	Abuwatfa *et al*., 2023
Secondary Treatment	Biological treatment where microorganisms break down organic matter into simpler compounds.	Effectively reduces organic pollutants.	Requires energy and space for aeration.	Secondary treatment plants.	Bala *et al*., 2022
Tertiary Treatment	Advanced filtration and disinfection methods to further remove remaining contaminants, including nutrients and pathogens.	Produces high-quality treated effluent.	High operational and maintenance costs.	Drinking water production.	Silva, 2023
Advanced Oxidation	Chemical treatment using oxidizing agents such as ozone or UV light to degrade organic and inorganic pollutants.	Effective in removing persistent compounds.	Expensive and requires skilled operation.	Industrial wastewater treatment.	Lupu *et al*., 2023
Membrane Filtration	Filtration through semi-permeable membranes to separate contaminants based on size and molecular weight.	Produces high-quality effluent with low TDS.	Prone to fouling and requires maintenance.	Desalination plants.	Mathew 2024a

Physical Treatment Processes of Wastewater: Physical treatment processes of wastewater include screening to remove large objects, sedimentation to settle out solids, and filtration to remove smaller particles. Flotation is used to separate oils and greases, while disinfection, although not purely physical, may also be employed. These processes are designed to physically separate contaminants from wastewater without altering their chemical composition. The treated water can then undergo further biological and chemical treatment to meet quality standards before being discharged or reused.

Screening of Wastewater Treatment Processes: Screening is a vital preliminary process in wastewater treatment, primarily focused on removing large solid debris and objects from the incoming wastewater. It serves to protect downstream equipment and processes from damage and clogging. The screening process involves the passage of wastewater through screens with openings of varying sizes. Coarse screens capture larger objects like sticks, rags, and plastics, while fine screens and microscreens trap smaller particles and debris. As wastewater flows through the screening chamber, solids are retained on the screen surface while the screened water passes through. The collected solids are then typically lifted or conveyed to a collection point for disposal. Regular maintenance of screening equipment is crucial to ensure optimal performance, including cleaning to prevent clogging and inspecting for damage or wear. The efficiency of screening depends on factors such as screen size, design, flow rate, and influent characteristics. Overall, screening plays a critical role in safeguarding wastewater treatment facilities, enhancing process efficiency, and ensuring the quality of treated effluent discharged into the environment or reused for various purposes (Zahmatkesh *et al*., 2022).

Sedimentation of Wastewater Treatment Processes: Sedimentation is a fundamental process in wastewater treatment that involves the settling of suspended solids and particles in water under the influence of gravity. This process occurs in sedimentation tanks or clarifiers, where wastewater flows slowly, allowing gravity to pull heavier solids to the bottom while clearer water rises to the top. During sedimentation, particles in the wastewater collide and aggregate, forming larger, denser flocs that settle more quickly. The settled solids form a layer of sludge at the bottom of the tank, which is periodically removed for further treatment or disposal. Sedimentation helps to reduce the concentration of suspended solids, organic matter, and other pollutants in wastewater, thereby improving the quality of effluent discharged from treatment plants. It also aids in the removal of settleable solids, such as grit and sand, which can cause abrasion and damage to downstream equipment if not removed. Efficient sedimentation is crucial for the overall performance of wastewater treatment processes, as it helps to clarify the water and prepare it for further treatment stages, such as filtration or biological treatment. Proper design, operation, and maintenance of sedimentation tanks are essential to ensure optimal sedimentation efficiency and the effective removal of solids from wastewater (Badawi *et al*., 2023).

Filtration of Wastewater Treatment Processes: Filtration is a key process in wastewater treatment that involves the removal of suspended solids and other impurities from wastewater by passing it through a porous medium. This medium, typically comprised of sand, gravel, or fabric, traps particles while allowing the treated water to pass through. In wastewater treatment plants, filtration can occur through various methods, including rapid sand filtration, slow sand filtration, multimedia filtration, and membrane filtration. Each method offers different levels of filtration efficiency and is chosen based on factors such as the quality of the influent wastewater and treatment requirements (Cescon, and Jiang, 2020). During filtration, suspended solids, organic matter, and microorganisms are physically captured by the filter medium, resulting in cleaner water. Filtration helps to improve water clarity, reduce turbidity, and remove pathogens and other harmful contaminants. Efficient filtration is essential for producing high-quality effluent that meets regulatory standards for discharge or reuse. Proper maintenance of filtration equipment is necessary to prevent clogging and ensure consistent performance. Overall, filtration plays a critical role in the wastewater treatment process by providing a final polishing step to remove remaining impurities before the treated water is discharged into the environment or reused for beneficial purposes (Maiyo *et al*., 2023).

Chemical Treatment Processes of Wastewater Treatment: Chemical treatment processes are vital in wastewater treatment for removing contaminants before discharge. Coagulation and flocculation involve adding chemicals like aluminum sulfate or ferric chloride to destabilize suspended particles, allowing them to form larger flocs that can be easily removed. Neutralization adjusts pH levels using lime or sulfuric acid to make wastewater less harmful. Disinfection, typically with chlorine or ozone, kills harmful pathogens. Precipitation removes heavy metals and phosphates by forming insoluble compounds. Advanced oxidation processes (AOPs) use powerful oxidants like hydrogen peroxide or UV radiation to break down organic pollutants. These chemical treatments are often combined with physical and biological processes for comprehensive wastewater treatment, ensuring compliance with environmental regulations and protecting public health (Badawi *et al*., 2023).

Coagulation and Flocculation: Coagulation and flocculation are essential processes in wastewater treatment for removing suspended particles and colloids. Coagulation involves the addition of chemicals known as coagulants, such as aluminum sulfate (alum) or ferric chloride, to destabilize the charged particles in the wastewater. These coagulants neutralize the electrical charges on the particles, allowing them to come together and form aggregates. Following coagulation, flocculation is employed to further enhance the aggregation of particles. During flocculation, gentle mixing or agitation is applied to the wastewater, promoting the formation of larger and denser particles called flocs (Badawi *et al*., 2023). This process encourages the collision and adhesion of smaller particles, resulting in the formation of larger and heavier flocs. The formed flocs are then allowed to settle out of the water through sedimentation or filtration processes. This separation step effectively removes the aggregated particles from the wastewater, leaving behind clearer water that can undergo further treatment. Coagulation and flocculation play a crucial role in the initial stages of wastewater treatment by improving the efficiency of subsequent processes such as sedimentation, filtration, and disinfection. These processes aid in reducing turbidity, removing suspended solids, and facilitating the removal of contaminants, thus ensuring the quality of treated wastewater meets regulatory standards before discharge into the environment (Kolya, and Kang, 2023).

Chemical Precipitation: Chemical precipitation is a key process in wastewater treatment for the removal of dissolved metals and ions, such as heavy metals and phosphates, from water. This method involves adding specific chemicals to the wastewater that react with the dissolved substances to form insoluble precipitates. These precipitates can then be separated from the water through sedimentation or filtration. Common chemicals used in chemical precipitation include lime (calcium hydroxide), ferric chloride, aluminum sulfate (alum), and sodium aluminate. The choice of chemical depends on the specific contaminants present in the wastewater and the desired treatment outcome (Liu *et al.*, 2023). For example, in the removal of heavy metals like lead, copper, and cadmium, chemicals such as lime or sodium hydroxide may be used to raise the pH of the wastewater, causing the metals to precipitate out as hydroxide compounds. Similarly, phosphates can be removed by adding chemicals like alum or ferric chloride, which react with phosphate ions to form insoluble precipitates. Once the precipitates are formed, they are allowed to settle out of the water, typically in a sedimentation basin. The clarified water can then undergo further treatment or be discharged safely into the environment. Chemical precipitation is an effective method for reducing the concentration of dissolved contaminants in wastewater, contributing to the overall purification of water resources and protection of ecosystems (Mathew *et al*., 2023c).

Biological Treatment Processes of Wastewater Treatment: Biological treatment processes in wastewater treatment utilize microorganisms to degrade organic pollutants and remove nutrients from wastewater. The two main types of biological treatment are aerobic and anaerobic processes. In aerobic treatment, oxygen is supplied to the microorganisms, typically through aeration, allowing them to metabolize organic matter into carbon dioxide, water, and biomass. This process, often carried out in activated sludge systems or aerobic bioreactors, effectively reduces the organic content of the wastewater. Anaerobic treatment occurs in the absence of oxygen and relies on anaerobic microorganisms to break down organic matter through fermentation and other anaerobic processes. This results in the production of methane gas and carbon dioxide, along with a reduction in organic pollutants. Both aerobic and anaerobic processes can also facilitate the removal of nutrients like nitrogen and phosphorus through microbial assimilation and conversion. Biological treatment processes play a crucial role in wastewater treatment by harnessing the natural capabilities of microorganisms to purify water and reduce environmental pollution (Bala *et al.*, 2022).

Activated Sludge Process: The activated sludge process is a biological treatment method used to remove organic pollutants from wastewater. In this process, wastewater is mixed with a culture of microorganisms (activated sludge) in an aeration tank. Oxygen is continuously supplied to the tank to create aerobic conditions, allowing the microorganisms to metabolize and degrade organic matter in the wastewater. During aeration, the microorganisms break down the organic pollutants into simpler, harmless substances such as carbon dioxide and water. After aeration, the wastewater and activated sludge mixture undergoes settling in a clarifier or settling tank, where the activated sludge settles to the bottom as sludge. A portion of this sludge is recycled back into the aeration tank to maintain microbial activity, while the excess sludge is removed for further treatment or disposal. The clarified effluent is then discharged or subjected to additional treatment before discharge into the environment. The activated sludge process effectively produces treated wastewater that meets regulatory standards for environmental discharge (Sharma *et al*., 2023).

Trickling Filters: Trickling filters are a biological treatment technology used in wastewater treatment to remove organic matter and suspended solids. They consist of a bed of porous media, such as rocks, gravel, or synthetic materials, through which wastewater is trickled or sprayed. The wastewater flows over the surface of the media, creating a thin film or "biofilm" where microbial communities develop and attach. As the wastewater passes through the biofilm, organic pollutants are metabolized and degraded by the microorganisms present in the biofilm. This biological process converts organic matter into simpler, less harmful substances, such as carbon dioxide and water. Trickling filters can operate under aerobic or anaerobic conditions, depending on the level of oxygen availability within the biofilm. Aerobic trickling filters require the continuous supply of oxygen to support microbial activity, while anaerobic trickling filters operate in the absence of oxygen. After passing through the trickling filter, the treated wastewater undergoes clarification to separate the treated effluent from any remaining suspended solids or biomass. The clarified effluent can then be discharged into receiving water bodies or subjected to further treatment processes. Trickling filters are an effective and economical method for biological wastewater treatment, particularly in smaller-scale or decentralized treatment systems (Koul *et al*., 2022).

Sequencing Batch Reactors: Sequencing Batch Reactors (SBRs) are advanced biological treatment systems used in wastewater treatment plants. Unlike continuous flow systems, SBRs operate in batches, performing multiple treatment steps within a single reactor. The SBR is filled with wastewater from the influent source, typically using pumps or gravity flow. Once filled, the reactor undergoes a series of treatment phases, including aeration, mixing, and settling. During the aerobic phase, air is introduced into the reactor to provide oxygen for microbial activity (Kalmakhanova *et al*., 2023). Microorganisms in the reactor metabolize and degrade organic pollutants present in the wastewater. After the reaction phase, the aeration is stopped, allowing suspended solids to settle to the bottom of the reactor. Once settling is complete, the clarified effluent is decanted from the top of the reactor, leaving behind the settled sludge. The reactor remains idle until the next batch cycle begins. SBRs offer several advantages, including flexibility in operation, efficient nutrient removal, and effective treatment of variable wastewater flows and characteristics. They are particularly suitable for small to medium-sized treatment plants and can achieve high treatment efficiencies while requiring relatively low maintenance (Parsa *et al*., 2024).

Advanced Treatment Processes of Wastewater Treatment: Advanced treatment processes in wastewater treatment are employed to further enhance the quality of treated wastewater before discharge into the environment. These processes target specific contaminants that may remain after conventional treatment methods. Membrane processes such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) use semi-permeable membranes to remove dissolved solids, organic compounds, and microorganisms from water. Activated carbon adsorption involves the use of porous carbon materials to adsorb organic pollutants, chemicals, and odors from wastewater, effectively removing them from the water (Zahmatkesh *et al*., 2022). Advanced Oxidation Processes utilize powerful oxidants such as ozone, hydrogen peroxide, or UV radiation to degrade and mineralize organic pollutants that are resistant to conventional treatment methods. Ion exchange processes remove specific ions from wastewater by exchanging them with ions of similar charge present on a resin material. Electrocoagulation involves the use of an electrical current to destabilize and coagulate suspended particles and dissolved contaminants, facilitating their removal from wastewater. These advanced treatment processes are often employed as tertiary treatment steps to ensure the treated wastewater meets stringent quality standards and regulatory requirements before discharge into surface waters or reuse for beneficial purposes (Capodaglio, 2020).

Membrane Filtration: Membrane filtration is a widely used advanced treatment process in wastewater treatment that employs semi-permeable membranes to separate particles, microorganisms, and dissolved contaminants from water. There are several types of membrane filtration processes, including reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF). In RO, high-pressure is applied to the wastewater, forcing it through a membrane that allows only water molecules to pass through, leaving behind dissolved salts, organic compounds, and other contaminants. This process effectively removes dissolved solids, pathogens, and most organic pollutants from the water. NF operates similarly to RO but with a slightly larger pore size, allowing some ions and smaller organic molecules to pass through while rejecting larger molecules and contaminants. NF is often used for the removal of specific ions and organic compounds (Othman *et al*., 2021). UF utilizes membranes with larger pores than RO and NF, allowing the passage of larger particles such as bacteria, viruses, and suspended solids while retaining macromolecules and colloidal particles. UF is effective for removing particulate matter, turbidity, and microorganisms from wastewater. Membrane filtration processes play a crucial role in producing high-quality treated water suitable for reuse, discharge into the environment, or further treatment for potable water production (Abuwatfa *et al*., 2023).

Ozonation: Ozonation is an advanced treatment process used in wastewater treatment for the removal of organic pollutants, microorganisms, and odor-causing compounds. It involves the generation and injection of ozone gas (O3) into the wastewater, where it reacts with contaminants through oxidation. During ozonation, ozone molecules decompose into highly reactive oxygen radicals, such as hydroxyl radicals (OH•), which attack and oxidize organic compounds present in the wastewater. This oxidation process breaks down complex organic molecules into simpler, less harmful substances such as carbon dioxide, water, and other byproducts. Ozonation is effective for removing a wide range of contaminants, including pharmaceuticals, pesticides, industrial chemicals, and pathogens. It also helps in reducing color, odor, and taste compounds in wastewater (Epelle *et al*., 2023). Additionally, ozonation can improve the efficiency of other treatment processes, such as biological treatment and filtration, by breaking down recalcitrant compounds and reducing the bioavailability of contaminants. However, ozonation can be energy-intensive and costly compared to other treatment methods. Proper consideration of factors such as wastewater composition, ozone dosage, and contact time is necessary to optimize the performance and cost-effectiveness of ozonation in wastewater treatment plants. Overall, ozonation is a valuable tool for achieving high-quality treated wastewater suitable for discharge or reuse in various applications (Derco *et al*., 2021).

Advanced Oxidation Processes: Advanced Oxidation Processes (AOPs) are advanced treatment methods used in wastewater treatment to degrade and remove persistent organic pollutants (POPs), pharmaceuticals, and other hazardous contaminants that are resistant to conventional treatment methods. AOPs utilize powerful oxidizing agents to generate highly reactive oxygen species (ROS) such as hydroxyl radicals (OH•) or other reactive oxygen intermediates. Some common AOPs include ozonation, UV irradiation, hydrogen peroxide (H_2O_2) oxidation, Fenton's reagent, and photo-Fenton processes. These processes generate ROS that react with organic pollutants, breaking down complex molecules into simpler, less harmful byproducts such as carbon dioxide, water, and mineral acids. AOPs are effective for degrading a wide range of contaminants, including dyes, pesticides, pharmaceuticals, and industrial chemicals. They can also remove pathogens and improve the overall quality of treated wastewater (Lupu *et al*., 2023). However, AOPs often require high energy inputs, specialized equipment, and careful control of reaction conditions. Optimizing AOPs involves considerations such as the selection of appropriate oxidants, pH control, reaction time, and reactor design to achieve efficient contaminant degradation. Despite their complexity and cost, AOPs are valuable tools for wastewater treatment plants facing challenges associated with emerging contaminants and stricter regulatory requirements, providing an effective means of achieving advanced water purification and environmental protection (Parsa *et al*., 2024).

Disposal Options for Treated Wastewater: This table 3 below provides a brief overview of the different disposal options, along with their respective advantages, disadvantages, and example applications. Keep in mind that the suitability of each option can vary depending on factors such as local regulations, environmental conditions, and treatment capabilities (Adetunji *et al*., 2023).

Table 3: Various disposal options for treated wastewater

Disposal Option	Description	Advantages	Disadvantages	Example Applications	References
Surface Water Discharge	Treated wastewater is released into rivers, lakes, or oceans.	Easy to implement	Potential environmental impact	Municipal wastewater treatment	Lemessa *et al*., 2023
Land Application	Treated wastewater is applied to land for irrigation or recharging groundwater.	Nutrient-rich for soil	Requires suitable land and monitoring	Agricultural irrigation	Khan *et al*., 2022
Reuse for Non-Potable Purposes	Treated wastewater is reused for activities like industrial processes, landscape irrigation, or toilet flushing.	Conserves freshwater resources	Requires separate distribution systems	Industrial facilities, golf courses	Abou-Shady *et al*., 2023
Groundwater Recharge	Treated wastewater is injected into groundwater aquifers.	Replenishes groundwater	Potential contamination risks	Aquifer recharge projects	Abd-Elaty *et al*., 2022
Evaporation Ponds	Treated wastewater is evaporated, leaving behind solids for disposal.	Low cost	Land-intensive	In arid regions with limited water resources	Alresheedi *et al*., 2023

Surface Water Discharge: Surface water discharge is a common method of disposing treated wastewater, involving the release of effluent into rivers, lakes, or oceans after undergoing treatment at wastewater treatment plants. This method is widely used in municipal wastewater treatment systems globally. The advantages of surface water discharge include its relative ease of implementation, as existing water bodies serve as natural conduits for the effluent. Additionally, it can help dilute pollutants and nutrients present in the treated wastewater, mitigating potential environmental impacts. However, there are also notable disadvantages associated with surface water discharge. One major concern is the potential environmental impact on aquatic ecosystems, as even treated wastewater may contain residual pollutants or excess nutrients that can disrupt natural habitats and lead to eutrophication (Silva, 2023). Furthermore, reliance on surface water discharge may exacerbate water scarcity issues in regions with limited freshwater resources, as treated wastewater is essentially lost to the natural water cycle rather than being reused.

Despite these drawbacks, surface water discharge remains a widely used disposal option due to its practicality and relatively low cost compared to alternative methods such as reuse or groundwater recharge. Effective monitoring and regulation are essential to ensure that surface water discharge does not compromise water quality or ecosystem health (Al-Addous *et al*., 2023).

Groundwater Recharge: Groundwater recharge involves the intentional introduction of treated wastewater into groundwater aquifers, replenishing underground water reserves. This method is employed in areas where groundwater depletion is a concern or where there is a need to manage excess treated wastewater sustainably. One of the key advantages of groundwater recharge is its potential to bolster dwindling groundwater levels, helping to sustain water supplies for drinking, agriculture, and industry. By injecting treated wastewater underground, recharge projects can also help prevent land subsidence and saltwater intrusion in coastal areas. However, groundwater recharge is not without its challenges. There are concerns about the quality of the treated wastewater and the potential for contaminants to leach into the aquifer, compromising water quality (Sherif *et al*., 2021; Mathew *et al*. 2024d). Effective treatment processes and rigorous monitoring are essential to mitigate these risks and ensure that recharged groundwater meets regulatory standards for potable use. Furthermore, the success of groundwater recharge projects depends on factors such as hydrogeological conditions, soil permeability, and the availability of suitable injection sites. Adequate infrastructure and management practices are necessary to optimize recharge efficiency and minimize environmental impacts. Overall, groundwater recharge offers a promising solution for sustainable water management, but careful planning and implementation are required to address technical, regulatory, and environmental considerations effectively (Masood *et al*., 2024).

Reuse and Recycle: The reuse and recycling of wastewater treatment effluent involve treating wastewater to a standard suitable for various non-potable purposes, such as industrial processes, landscape irrigation, and toilet flushing, instead of discharging it into the environment. This approach conserves freshwater resources and reduces the strain on water supplies by providing an alternative source of water for non-drinking purposes. One of the primary advantages of wastewater reuse is its potential to alleviate water scarcity and mitigate the demand for freshwater resources, particularly in regions facing drought or rapid population growth. Additionally, by diverting treated wastewater from surface water bodies, reuse can help reduce pollution and minimize environmental degradation (Abou-Shady *et al*., 2023; Mathew *et al*. 2024e). However, there are also challenges associated with wastewater reuse and recycling. Treatment processes must effectively remove contaminants and pathogens to meet the required quality standards for the intended reuse applications. Additionally, establishing separate distribution systems for recycled water and ensuring public acceptance and regulatory compliance can be logistical and financial hurdles. Despite these challenges, wastewater reuse and recycling offer significant benefits for sustainable water management, supporting the efficient use of resources and promoting environmental stewardship. Continued advancements in treatment technologies and regulatory frameworks can further enhance the viability and acceptance of wastewater reuse as a valuable component of integrated water resource management strategies (Bauer and Wagner, 2022).

Land Application: Land application of wastewater treatment effluent involves the controlled application of treated wastewater onto land surfaces for various purposes, such as irrigation, soil amendment, and groundwater recharge. This method utilizes the nutrient-rich content of treated wastewater to support agricultural productivity and enhance soil fertility. One of the primary advantages of land application is its potential to provide a sustainable and cost-effective solution for wastewater disposal while simultaneously benefiting agricultural activities. Treated wastewater can serve as a valuable source of nutrients, organic matter, and moisture for crops, helping to improve soil structure and fertility. Additionally, land application can contribute to groundwater recharge by allowing treated wastewater to percolate through the soil, replenishing aquifers and supporting sustainable water supplies (Khan *et al*., 2022). However, there are also potential challenges and risks associated with land application. These include the potential for nutrient runoff and groundwater contamination if not managed properly, as well as concerns about the presence of pathogens and contaminants in the treated wastewater. Effective management practices, including appropriate monitoring, soil testing, and application rates, are essential to mitigate these risks and ensure the safe and sustainable use of treated wastewater for land application purposes. Overall, land application offers a promising opportunity to integrate wastewater treatment with agricultural practices, promoting resource efficiency and environmental sustainability in water management (Akhtar *et al*., 2021).

Sludge Management: Sludge management is a crucial aspect of wastewater treatment that involves the proper handling, treatment, and disposal of the solid residue generated during the treatment process. This sludge, often containing organic matter, pathogens, and other contaminants removed from the wastewater, requires careful management to prevent environmental pollution and ensure public health and safety. One common method of sludge management is dewatering, which involves removing excess water from the sludge to reduce its volume and facilitate further treatment or disposal (Silva, 2023). Dewatered sludge can then undergo various treatment processes, such as stabilization (e.g., anaerobic digestion, composting) to reduce its organic content and pathogens, making it safer for disposal or beneficial reuse. Disposal options for treated sludge include landfilling, where it is deposited in designated facilities, or incineration, which can reduce its volume and destroy pathogens through combustion. However, increasing emphasis is placed on sustainable alternatives such as land application, where treated sludge is applied to land as a soil conditioner or fertilizer, or energy recovery through anaerobic digestion to produce biogas. Effective sludge management requires careful planning, regulatory compliance, and consideration of environmental impacts to ensure the safe and sustainable handling of wastewater treatment by-products. Integrated approaches that prioritize resource recovery and minimize environmental risks are essential for advancing sustainable sludge management practices (Koul *et al*., 2022).

Environmental Impacts and Sustainability: The table 4 provides a concise overview of the environmental impacts associated with wastewater treatment and the sustainability considerations necessary to mitigate these impacts. Effective wastewater management strategies should prioritize minimizing environmental harm while promoting resource efficiency and ecosystem protection (Adetunji *et al*., 2021).

Table 4: The environmental impacts and sustainability aspects of wastewater treatment

Aspect	Description	Environmental Impacts	Sustainability Considerations	References
Water Quality	The treatment process aims to remove contaminants from wastewater, improving water quality.	Reduction of pollutants, pathogens, and toxins	Conserving water resources, protecting aquatic ecosystems	Silva, 2023
Energy Consumption	Wastewater treatment facilities require energy for various processes, contributing to carbon emissions.	Greenhouse gas emissions, reliance on fossil fuels	Implementing energy-efficient technologies, utilizing renewable energy sources	Goliopoulos *et al*., 2022
Sludge Management	The handling and disposal of sludge generated during treatment can have environmental impacts.	Potential for land and water pollution	Implementing sludge treatment and reuse strategies, minimizing waste generation	Sugurbekova *et al*., 2023
Habitat and Ecosystem Impact	Discharge of treated effluent and disposal of by-products can affect terrestrial and aquatic habitats.	Alteration of ecosystems, eutrophication	Implementing habitat restoration, adopting eco-friendly treatment methods	Dai *et al*., 2023

Conclusion: Wastewater management is a critical aspect of environmental stewardship and public health. This review has provided an overview of wastewater characteristics, treatment methods, and disposal options, highlighting the complexity and importance of managing this ubiquitous byproduct of human activity. Wastewater varies widely in composition, depending on its source and the activities it has been exposed to. Effective treatment processes are essential to remove pollutants, pathogens, and nutrients, ensuring that discharged effluent meets regulatory standards and does not pose a risk to human health or the environment. Various treatment technologies, ranging from physical and chemical processes to biological treatments, offer versatile approaches to wastewater treatment. These methods must be tailored to the specific characteristics of the wastewater and the desired quality of the treated effluent. Furthermore, the selection of appropriate disposal options, such as surface water discharge, land application, or groundwater recharge, requires careful consideration of environmental impacts, regulatory requirements, and sustainability considerations. Overall, integrated approaches that prioritize pollution prevention, resource recovery, and ecosystem protection are essential for sustainable wastewater management. Continued research, innovation, and collaboration are needed to address emerging challenges and ensure the long-term viability of wastewater treatment and disposal practices.

REFERENCES

Abd-Elaty, I; Abd-Elmoneem, SM; Abdelaal, GM; Vrána, J; Vranayová, Z; Abd-Elhamid, HF (2022). Groundwater Quality Modeling and Mitigation from Wastewater Used in Irrigation, a Case Study of the Nile Delta Aquifer in Egypt. *Int. J. Environ. Res. and pub. Health*, *19*(22): 14929. https://doi.org/10.3390/ijerph192214929

Abou-Shady, A; Siddique, MS; Yu, W (2023). A Critical Review of Recent Progress in Global Water Reuse during 2019–2021 and Perspectives to Overcome Future Water Crisis. *Environ.*, *10*: 159. https://doi.org/10.3390/environments10090159

Abuwatfa, WH; AlSawaftah, N; Darwish, N; Pitt, WG; Husseini, GA. (2023). A Review on Membrane Fouling Prediction Using Artificial Neural Networks (ANNs). *Memb.; 13*(7): 685. https://doi.org/10.3390/membranes13070685

Adetunji CO, Inobeme A., Singh KRB, Olaniyan O, Mathew JT, Singh J, Vanya N; Singh RP. (2021). Waterborne Polyurethanes for Sensors: In Book; Eco-Friendly Waterborne Polyurethanes. American Chemical Society: Washington, DC, O., 333- 353. doi: 10.1201/9781003173526-20.

Adetunji, CO; Akinbo, O; Mathew, JT; Egbuna, C; Inobeme, A; Olotu, TM; Ajayi, OO; Dauda, W; Ghazanfar, S; Ogundolie, FA; Adetunji, JB; Adetuyi, BO; Ajenifujah-Solebo, SO; Aborode, AT. (2024)b. Nanotechnology: History, Trends and Modern Applications. In book: Handbook of Agricultural Biotechnology, John Wiley and Sons, 1-17. DOI: 10.1002/9781119836513.ch1

Adetunji, CO; Mathew, JT; Inobeme, A; Taiwo, O; Olaniyan, O; Shakira, G; Wadazani, D (2024)a. Application of Biosensors for Detection and Monitoring of Water Quality. In book: Organic and Inorganic Materials Based Sensors, John Wiley and Sons, Inc.; 1065-1077, DOI: 10.1002/9783527834266.ch46

Adetunji, CO; Olaniyan, OT; Inobeme, A; Adeyomoye, O; Mathew, JT; Akinbo, O (2023). Recent Advances in the Characterization and Application of Graphene in the Food Industry. In book: Sensing and Artificial Intelligence Solutions for Food Manufacturing. CRC Press, 153-164. doi: 10.1201/9781003207955-11

Akhtar, N; Syakir Ishak, MI; Bhawani, SA; Umar, K (2021). Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. *Water*, *13*: 2660. https://doi.org/10.3390/w13192660

Al-Addous, M; Bdour, M; Alnaief, M; Rabaiah, S; Schweimanns, N (2023). Water Resources in Jordan: A Review of Current Challenges and Future Opportunities. *Water*, *15:* 3729. https://doi.org/10.3390/w15213729

Al-Addous, M; Bdour, M; Alnaief, M; Rabaiah, S; Schweimanns, N (2023). Water Resources in Jordan: A Review of Current Challenges and Future Opportunities. *Water*, *15*, 3729. https://doi.org/10.3390/w15213729

Al-Hamedi, FH; Kandhan, K; Liu, Y; Ren, M; Jaleel, A; Alyafei, MAM. (2023). Wastewater Irrigation: A Promising Way for Future Sustainable Agriculture and Food Security in the United Arab Emirates. *Water*, *15*: 2284. https://doi.org/10.3390/w15122284

Allioui, H; Mourdi, Y (2023). Exploring the Full Potentials of IoT for Better Financial Growth and Stability: A Comprehensive Survey. *Sens.; 23*: 8015. https://doi.org/10.3390/s23198015

Alresheedi, MT; Haider, H; Albuaymi, AM; AlSaleem, SS; Shafiquzzaman, M; Alharbi, A; Ahsan, A. (2023). Sustainability of a Low-Cost Decentralized Treatment System for Wastewater Reuse: Resident Perception-Based Evaluation for Arid Regions. *Water*, *15*: 3458. https://doi.org/10.3390/w15193458

Arcangeli, G; Lulli, LG; Traversini, V; De Sio, S; Cannizzaro, E; Galea, RP; Mucci, N. (2022). Neurobehavioral Alterations from Noise Exposure in Animals: A Systematic Review. *Int. J. Env. Res. Pub. Health.; 20*(1): 591. https://doi.org/10.3390/ijerph20010591

Aziz, KH; Mustafa, FS; Omer, KM; Hama, S; Hamarawf, RF; Rahman, KO. (2023). Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. *RSC Adv.; 13*(26): 17595–17610. https://doi.org/10.1039/d3ra00723e

Badawi, AK; Salama, RS; Mostafa, MMM. (2023). Natural-based coagulants/flocculants as sustainable market-valued products for industrial wastewater treatment: a review of recent developments. *RSC Adv.; 13*(28): 19335–19355. https://doi.org/10.1039/d3ra01999c

Bala, S; Garg, D; Thirumalesh, BV; Sharma, M; Sridhar, K; Inbaraj, BS; Tripathi, M. (2022). Recent Strategies for Bioremediation of Emerging

Pollutants: A Review for a Green and Sustainable Environment. *Tox.; 10*(8): 484. https://doi.org/10.3390/toxics10080484

Bauer, S; Wagner, M. (2022). Possibilities and Challenges of Wastewater Reuse—Planning Aspects and Realized Examples. *Water, 14,* 1619. https://doi.org/10.3390/w14101619

Capodaglio, AG. (2020). Critical Perspective on Advanced Treatment Processes for Water and Wastewater: AOPs, ARPs, and AORPs. *Appl. Sci.; 10*: 4549. https://doi.org/10.3390/app10134549

Capodaglio, AG. (2023). Biorefinery of Sewage Sludge: Overview of Possible Value-Added Products and Applicable Process Technologies. *Water, 15:* 1195. https://doi.org/10.3390/w15061195

Cescon, A; Jiang, JQ. (2020). Filtration Process and Alternative Filter Media Material in Water Treatment. *Water, 12*, 3377. https://doi.org/10.3390/w12123377

Dai, T; Liu, R; Zhou, X; Zhang, J; Song, M; Zou, P; Bi, X; Li, S. (2023). Role of Lake Aquatic-Terrestrial Ecotones in the Ecological Restoration of Eutrophic Water Bodies. *Tox., 11*(7): 560. https://doi.org/10.3390/toxics11070560

Derco, J; Gotvajn, AŽ; Čižmárová, O; Dudáš, J; Sumegová, L; Šimovičová, K. (2021). Removal of Micropollutants by Ozone-Based Processes. *Proc.; 9*: 1013. https://doi.org/10.3390/pr9061013

Epelle, EI; Macfarlane, A; Cusack, M; Burns, A; Okolie, JA; Mackay, W; Rateb, M; Yaseen, M. (2023). Ozone application in different industries: A review of recent developments. *Chem. Engin. J.; 1996), 454*: 140188. https://doi.org/10.1016/j.cej.2022.140188

Godyń, I; Bodziony, M; Grela, A; Muszyński, K; Pamuła, J. (2022). Determination of Pollution and Environmental Risk Assessment of Stormwater and the Receiving River, Case Study of the Sudół River Catchment, Poland. *International journal of environmental research and public health, 20*(1): 504. https://doi.org/10.3390/ijerph20010504

Goliopoulos, N; Mamais, D; Noutsopoulos, C; Dimopoulou, A; Kounadis, C. (2022). Energy Consumption and Carbon Footprint of Greek Wastewater Treatment Plants. *Water, 14*: 320. https://doi.org/10.3390/w14030320

Inobeme, A, Nayak, V, Mathew JT, Okonkwo, S, Ekwoba, L, Ajai, AI, Bernard, E, Inobeme, J, Agbugui, MM. Singh, KRB. (2022). Chemometric approach in environmental pollution analysis: A critical review. *Journal of Environmental Management,* 309 (114653), 1-18. https://doi.org/10.1016/j.jenvman.2022.114653

Inobeme, A; Mathew, JT; Adetunji, CO; Ajai, A.I; Inobeme, J; Maliki, M; Okonkwo, S; Adekoya, MA; Bamigboye, MO; Jacob, JO; Eziukwu, CA. (2023)a. Recent advances in nanotechnology for remediation of heavy metals. *Environm. Monit. Assess.;* 195(111): 1-24. DOI: https://doi.org/10.1007/s10661-022-10614-7.

Inobeme, A; Mathew, JT; Jatto, E; Inobeme, J; Adetunji, CO; Muniratu, M; Onyeachu, BI; Adekoya, MA; Ajai, AI; Mann, A; Olori, E; Akhor, SO; Eziukwu, CA; Kelani, T; Omali, PI. (2023)b. Recent advances in instrumental techniques for heavy metal quantification. *Environ. Monit. and assess.; 195*(4): 452. DOI: https://doi.org/10.1007/s10661-023-11058-3.

Inobeme, A; Ajai, AI.; Adetunji, CO; Inobeme, J; Maliki, M; Shaba, EY; Osarenre, EJ; Mathew, JT; Eziukwu, CA; Kelani, T; Bamigboye, O; Okonkwo, S. (2023)c. Wastewater Treatment Technologies. In book: Industrial Wastewater Reuse: Applications, Prospects and Challenges. Springer Nature Singapore, 201-213. DOI: 10.1007/978-981-99-2489-9_10.

Inobeme, A; Adetunji, CO; Ajai, AI; Inobeme, J; Mathew, JT; Obar, A; Maliki, M; Nwakife, N; Eziukwu, C. (2023)d. Chemical Nanosensors for Monitoring Environmental Pollution. In book: Advanced Application of Nanotechnology to Industrial Wastewater, Springer Nature Singapore, 93-103. DOI: 10.1007/978-981-99-3292-4_6.

Kalair, AR; Seyedmahmoudian, M; Stojcevski, A; Abas, N; Khan, N. (2021). Waste to energy conversion for a sustainable future. *Heliyon, 7*(10): e08155. https://doi.org/10.1016/j.heliyon.2021.e08155

Kalmakhanova, MS; Diaz de Tuesta, JL; Malakar, A; Gomes, HT; Snow, DD. (2023). Wastewater Treatment in Central Asia: Treatment Alternatives for Safe Water Reuse. *Sustain.; 15*: 14949. https://doi.org/10.3390/su152014949.

Khan, MM; Siddiqi, SA; Farooque, AA; Iqbal, Q.; Shahid, SA; Akram, MT; Rahman, S; Al-Busaidi, W; Khan, I. (2022). Towards Sustainable Application of Wastewater in Agriculture: A Review on Reusability and Risk Assessment. *Agron.*, *12*: 1397. https://doi.org/10.3390/agronomy12061397

Kokina, K; Mezule, L; Gruskevica, K; Neilands, R; Golovko, K; Juhna, T. (2022). Impact of Rapid pH Changes on Activated Sludge Process. *Appl. Sci.; 12*: 5754. https://doi.org/10.3390/app12115754

Kolya, H; Kang, CW. (2023). Bio-Based Polymeric Flocculants and Adsorbents for Wastewater Treatment. *Sustain. 15*, 9844. https://doi.org/10.3390/su15129844

Koul, B; Yadav, D; Singh, S; Kumar, M; Song, M. (2022). Insights into the Domestic Wastewater Treatment (DWWT) Regimes: A Review. *Water, 14*: 3542. https://doi.org/10.3390/w14213542

Kumar, R; Verma, A; Shome, A; Sinha, R; Sinha, S; Jha, PK; Kumar, R; Kumar, P; Shubham; Das, S; *et al*. (2021). Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions. *Sustain. 13*, 9963. https://doi.org/10.3390/su13179963

Lemessa, F; Simane, B Seyoum, A.; Gebresenbet, G. (2023). Assessment of the Impact of Industrial Wastewater on the Water Quality of Rivers around the Bole Lemi Industrial Park (BLIP), Ethiopia. *Sustain. 15*: 4290. https://doi.org/10.3390/su15054290

Liu, Y; Wang, H; Cui, Y; Chen, N. (2023). Removal of Copper Ions from Wastewater: A Review. *International journal of environmental research and public health*, *20*(5): 3885. https://doi.org/10.3390/ijerph20053885

Lupu, GI; Orbeci, C; Bobirică, L; Bobirică, C; Pascu, LF. (2023). Key Principles of Advanced Oxidation Processes: A Systematic Analysis of Current and Future Perspectives of the Removal of Antibiotics from Wastewater. *Catal.; 13*: 1280. https://doi.org/10.3390/catal13091280

Maiyo, JK; Dasika, S; Jafvert, CT. (2023). Slow Sand Filters for the 21st Century: A Review. *International journal of environmental research and public health*, *20*(2): 1019. https://doi.org/10.3390/ijerph20021019

Manisalidis, I; Stavropoulou, E; Stavropoulos, A; Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review. *Front. Pub. Health*, *8*; 14. https://doi.org/10.3389/fpubh.2020.00014

Masood, MU; Rashid, M; Haider, S; Naz, I; Pande, CB; Heddam, S; Alshehri, F; Elkhrachy, I; Ahsan, A; Sammen, SS. (2024). Exploring Groundwater Quality Assessment: A Geostatistical and Integrated Water Quality Indices Perspective. *Water*, *16*, 138. https://doi.org/10.3390/w16010138

Mathew, JT; Inobeme, A; Musah, M.; Azeh, Y.; Abdullahi, A.; Shaba EY; Salihu, AM; Muhammad, EB; Josiah, JG; Jibrin, NA; Ismail, H; Muhammad, AI; Maurice, J; Mamman, A; Ndamitso, MM. (2024)a. A Critical Review of Green Approach on Wastewater Treatment Strategies. . *J. Appl. Sci. Environ. Manag.;* 28(2): 363-391. DOI: https://dx.doi.org/10.4314/jasem.v28i2.9

Mathew, JT; Inobeme, A; Abdulkadir, A; Etsuyankpa, MB; Shaba, EY; Musah, M; Azeh, Y; Adetunji, CO; Ibrahim, AM; Tanko, E; Mamman, A. (2024)b. Properties and Characteristics of Nanocoatings for Medicinal Applications. In book: Sustainable Approach to Protective Nanocoatings. IGI Global; publishing Tomorrow's Research Today, 203-227. DOI: 10.4018/979-8-3693-3136-1.ch007

Mathew, JT; Adetunji, CO; Inobeme, A; Musah, M; Azeh, Y; Otori, AA; Mamman, A. (2024)c. Nutritional Qualities of Agricultural Crops After Application of Nanobioherbicides. In book: Handbook of Agricultural Biotechnology, John Wiley and Sons, 3, 189-204, DOI: 10.1002/9781119836513.ch9

Mathew, JT; Musah, M; Azeh, Y; Muhammed, M. (2024) d. Development of Fe3O4 Nanoparticles for the Removal of Some Toxic Metals from Pharmaceutical Wastewater. Caliphate Journal of Science and Technology (CaJoST), 6(1), 26-34. DOI: https://dx.doi.org/10.4314/cajost.v6i1.4

Mathew, JT; Inobeme, A; Adetuyi, BO; Adetunji, CO; Popoola, OA; Olaitan, FY; Akinbo, O; Shahnawaz, M; Oyewole, OA; Eniola, KIT; Yerima, BM.

(2024)e. General Introduction of Microplastic: Uses, Types, and Generation. In book: Microplastic Pollution. Springer, Singapore, 1, 3-21. DOI: 10.1007/978-981-99-8357-5_1

Mathew, JT; Musah, M; Azeh, Y; Muhammed, M. (2023)a. Kinetic Study of Heavy Metals Removal from Pharmaceutical Wastewater Using Geopolymer/Fe_3O_4 Nanocomposite. Bima J. Sci. and Techn.; 7(4): 152- 163. DOI: 10.56892/bima.v7i4.539.

Mathew, JT**;** Musah, M; Azeh, Y; Muhammed, M. (2023)b. Adsorptive Removal of Selected Toxic Metals from Pharmaceutical Wastewater using Fe_3O_4/ZnO Nanocomposite, *Dutse J. Pure Appl. Sci.;* 9(4a): 236- 248. Doi: https://dx.doi.org/10.4314/dujopas.v9i4a.22.

Mathew, JT; Adetunji, CO; Inobeme, A; Musah, M; Azeh, Y; Otori, AA; Shaba, EY; Mamman, A; Tanko, E. (2023)c. Removal of Heavy Metals Using Bio-remedial Techniques. Springer Nature Switzerland AG 2023 M. P. Shah (ed.), Modern Approaches in Waste Bioremediation, 117-130. https://doi.org/10.1007/978-3-031-24086-7_6.

Münzel, T; Hahad, O; Daiber, A; Landrigan, PJ. (2023). Soil and water pollution and human health: what should cardiologists worry about?. *Cardiovascular research*, *119*(2): 440–449. https://doi.org/10.1093/cvr/cvac082

Muttil, N; Nasrin, T; Sharma, AK. (2023). Impacts of Extreme Rainfalls on Sewer Overflows and WSUD-Based Mitigation Strategies: A Review. *Water*, *15*: 429. https://doi.org/10.3390/w15030429

Nwokolo, SC; Meyer, EL; Ahia, CC. (2023). Credible Pathways to Catching Up with Climate Goals in Nigeria. *Clim.; 11*, 196. https://doi.org/10.3390/cli11090196

Olorunsola, A; Adetunji, CO; Olaniyan, O; Adetunji, JB; Akinbo, K; Adetuyi, BO; Inobeme, A; Mathew, JT; Ajenifujah-Solebo, SO. (2024). Application of Nanotechnology for the Production of Biopesticides, Bioinsecticides, Bioherbicides, Mosquitoe Repellants and Biofungicides. In book: Handbook of Agricultural Biotechnology, John Wiley and Sons, 293-309. DOI: 10.1002/9781119836483.ch11

Onyando, ZO; Omukunda, E; Okoth, P; Khatiebi, S; Omwoma, S; Otieno, P; Osano, O; Lalah, J. (2023). Screening and Prioritization of Pesticide Application for Potential Human Health and Environmental Risks in Largescale Farms in Western Kenya. *Agric.; 13*: 1178. https://doi.org/10.3390/agriculture13061178

Othman, NH; Alias, NH; Fuzil, NS; Marpani, F; Shahruddin, MZ; Chew, CM; David Ng, KM; Lau, WJ; Ismail, AF. (2021). A Review on the Use of Membrane Technology Systems in Developing Countries. *Memb.; 12*(1): 30. https://doi.org/10.3390/membranes12010030

Parsa, Z; Dhib, R; Mehrvar, M. (2024). Dynamic Modelling, Process Control, and Monitoring of Selected Biological and Advanced Oxidation Processes for Wastewater Treatment: A Review of Recent Developments. *Bioengin.; 11*: 189. https://doi.org/10.3390/bioengineering11020189

Parsa, Z; Dhib, R; Mehrvar, M. (2024). Dynamic Modelling, Process Control, and Monitoring of Selected Biological and Advanced Oxidation Processes for Wastewater Treatment: A Review of Recent Developments. *Bioeng.; 11*: 189. https://doi.org/10.3390/bioengineering11020189

Priya, AK; Muruganandam, M; Ali, SS; Kornaros, M. (2023). Clean-Up of Heavy Metals from Contaminated Soil by Phytoremediation: A Multidisciplinary and Eco-Friendly Approach. *Toxics*, *11*(5): 422. https://doi.org/10.3390/toxics11050422

Rashid, A; Schutte, BJ; Ulery, A; Deyholos, MK; Sanogo, S; Lehnhoff, EA; Beck, L. (2023). Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health. *Agron.; 13*: 1521. https://doi.org/10.3390/agronomy13061521

Sharma, M; Agarwal, S; Agarwal Malik, R; Kumar, G; Pal, DB; Mandal, M; Sarkar, A; Bantun, F; Haque, S; Singh, P; Srivastava, N; Gupta, VK. (2023). Recent advances in microbial engineering approaches for wastewater treatment: a review. *Bioengineered*, *14*(1): 2184518. https://doi.org/10.1080/21655979.2023.2184518

Shen, Y; Zhang, X. (2024). Blue Sky Protection Campaign: Assessing the Role of Digital Technology in Reducing Air Pollution. *Systems*, *12*: 55. https://doi.org/10.3390/systems12020055

Sherif, M; Sefelnasr, A; Ebraheem, AA; Al Mulla, M; Alzaabi, M; Alghafli, K. (2021). Spatial and Temporal Changes of Groundwater Storage in the Quaternary Aquifer, UAE. *Water*, *13*, 864. https://doi.org/10.3390/w13060864

Silva, JA. (2023). Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. *Sustain. 15*: 10940. https://doi.org/10.3390/su151410940

Sugurbekova, G; Nagyzbekkyzy, E; Sarsenova, A; Danlybayeva, G; Anuarbekova, S; Kudaibergenova, R; Frochot, C; Acherar, S; Zhatkanbayev, Y; Moldagulova, N. (2023). Sewage Sludge Management and Application in the Form of Sustainable Fertilizer. *Sustain. 15*: 6112. https://doi.org/10.3390/su15076112

Witek-Krowiak, A; Gorazda, K; Szopa, D; Trzaska, K; Moustakas, K; Chojnacka, K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered*, *13*(5): 13474–13506. https://doi.org/10.1080/21655979.2022.2077894

Zahmatkesh, S; Amesho, KTT; Sillanpää, M. (2022). A critical review on diverse technologies for advanced wastewater treatment during SARS-CoV-2 pandemic: What do we know?. *J. Hard. Mat. Adv.; 7*: 100121. https://doi.org/10.1016/j.hazadv.2022.100121

Zhang, P; Yang, M; Lan, J; Huang, Y; Zhang, J; Huang, S; Yang, Y; Ru, J. (2023). Water Quality Degradation Due to Heavy Metal Contamination: Health Impacts and Eco-Friendly Approaches for Heavy Metal Remediation. *Toxics*, *11*: 828. https://doi.org/10.3390/toxics11100828

Zhu, Y; Han, S; Zhang, Y; Huang, Q. (2021). Evaluating the Effect of Government Emission Reduction Policy: Evidence from Demonstration Cities in China. *Inter. J. Environ. Res. Public. Health. 18*(9): 4649. https://doi.org/10.3390/ijerph18094649