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A Critical Review of Green Approach on Wastewater Treatment Strategies

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ABSTRACT: Green approach on wastewater treatment strategies aims to promote sustainable and environmentally friendly methods for treating wastewater while also reducing the environmental impact of traditional wastewater treatment processes. Hence, the objective of this paper was to undertake a critical review of green approach on wastewater treatment strategies using standard techniques of harvesting data from secondary sources from 2015 to 2023. Information obtained reveals that energy-efficient treatment technologies, such as anaerobic digestion and membrane bioreactors, use less energy than traditional treatment technologies. Treating wastewater for reuse can reduce the demand for freshwater resources and the energy required for water treatment. Onsite wastewater treatment systems, such as septic systems and composting toilets, can reduce the amount of wastewater that needs to be transported and treated at centralized facilities. Incorporating green infrastructure, such as rain gardens and permeable pavement, into urban areas can help reduce the amount of stormwater runoff that enters the wastewater treatment system. Extracting nutrients, such as nitrogen and phosphorus, from wastewater can be used as a fertilizer for crops, reducing the need for synthetic fertilizers. Overall, these green wastewater treatment strategies aim to reduce the energy consumption, chemical usage, and environmental impact of traditional wastewater treatment processes, while promoting sustainable and efficient use of resources

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Water is an essential resource that is required to sustain life. Its availability has to be adequate, safe and easily accessible. Current trends in climate change and rise in human population has compromised water

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adequacy, availability and safety. Wastewater managers around the world have the responsibility to ensure that the effluent that is eventually released into the environment does not degrade the quality of the recipient water bodies. Attaining sustainability in wastewater management is top in the of Sustainable Development Goals' Agenda. All in all, the realization of a more sustainable wastewater management will require a highly holistic and balanced approach in evaluating a particular management strategy's overall sustainability. Promoting the use of safe, affordable and adequately available wastewater treatment techniques is a step towards wastewater management for sustainability. This review paper therefore discusses some of the currently known and emerging wastewater management techniques that are considered essential in attaining sustainability in water resource management (Carrard e*t al*., 2019; Zapata-Mendoza e*t al*., 2022). Wastewater treatment is the process of removing contaminants from wastewater, making it safe to release back into the environment. The traditional approach to wastewater treatment has been focused on removing harmful substances, such as organic matter and pathogens, from wastewater using physical, chemical, and biological processes. In recent years, there has been a growing recognition of the importance of adopting a green approach to wastewater treatment. This approach aims to not only remove harmful substances from wastewater but also to use sustainable and eco-friendly methods to do so (Abuhasel e*t al*., 2021; Ahmed e*t al*., 2022). The green approach on wastewater treatment strategies involves the use of sustainable and environmentally friendly methods to treat wastewater. The aim of this approach is to reduce the environmental impact of wastewater treatment processes and promote the efficient use of resources. Traditionally, wastewater treatment plants use chemical and energy-intensive processes to treat wastewater, which can have negative impacts on the environment. However, the green approach on wastewater treatment strategies uses technologies that are designed to reduce the environmental impact of wastewater treatment (Guo e*t al*., 2019; Tóth e*t al*., 2022). Wastewater treatment is the process of removing pollutants and contaminants from water before it is discharged into the environment. The traditional approach to wastewater treatment has been focused on chemical and physical processes that are often energy-intensive and have a high environmental impact. However, a growing awareness of environmental issues has led to the development of new, more sustainable approaches to wastewater treatment (Mahmood e*t al*., 2022).

One example of a green approach on wastewater treatment is the use of constructed wetlands. These are man-made systems that mimic natural wetlands and use plants and microorganisms to remove pollutants from wastewater. Constructed wetlands are low-maintenance energy-efficient, and can treat large volumes of wastewater. Another example of a green approach on wastewater treatment is the use of anaerobic digestion. Anaerobic digestion is a biological process that converts organic matter in wastewater into biogas and nutrient-rich sludge. The biogas can be used as a renewable energy source, while the sludge can be used as a fertilizer (Oscar, and Caren, 2021; Gabr *et al*., 2023). In recent decades, a great deal of thorough research has been done on a novel technology called bioremediation of different waste waters. The demand for water has increased globally due to factors such as urbanization, industrialization expanding populations, sophisticated farming methods, and diverse uses of water. Wastewater is generated in large quantities as a result of many agricultural and industrial processes as well as daily human activity. The majority of urban wastewater produced in Indian cities is released into natural aquatic habitats untreated due to a lack of adequate management and treatment facilities. Due to the high volume of wastewater and the need for a vast treatment area, municipal sewage problems are more complicated. Although a number of methods have been suggested for efficient wastewater treatment, bioremediation is the most useful management tool for reducing environmental pollution and enhancing damaged locations (Akhtar e*t al*., 2021; Pathak e*t al*., 2022). This study examined the bioremediation of wastewater using microorganisms. The objective was to guarantee the improved transfer of results from laboratory-based bioremediation trials to field applications, which is presently insufficient. It has been demonstrated that bioremediation may effectively remove or significantly lower the quantities of numerous contaminants present in both municipal and industrial effluents using specific bacteria and empirical research. Results showed that the effectiveness of bioremediation varies depending on the microorganisms employed, the properties of the wastewater that needs to be cleaned, and the physical, chemical, and biological features of the contaminated area. Additionally, it has been shown that microbe incompatibility with the pollutant can inhibit enzyme activity, produce hazardous compounds, and slow down microbial metabolism, all of which can prolong bioremediation processes and lower the efficacy of the resulting decontamination (Bala e*t al*., 2022; Goh e*t al*., 2023). This review suggested using innovations like bio-stimulation and bioaugmentation for improved pollutant biodegradation as a way to get around these obstacles. Furthermore, it was discovered that increasing the intrinsic qualities of bioremediators toward resistant contaminants by genetic engineering increased their efficacy. To enhance bioremediation results in the future, the assessment also recommended using consortiums and a variety of bioremediation techniques. Therefore, bioremediation has a great deal of potential for removing contaminants from wastewater, and advancements in biotechnology may even further enhance the results of its field implementation (Patel e*t al*., 2020).

Overall, the green approach on wastewater treatment strategies aims to promote sustainable and environmentally friendly methods for treating wastewater while also reducing the environmental impact of traditional wastewater treatment processes.

Use of Natural Treatment Systems of Green Wastewater: Green wastewater, which refers to wastewater from agricultural activities or food processing, can be treated using natural treatment systems. Some of the natural treatment systems that can be used for green wastewater treatment include (Figure 1 and Table 1).

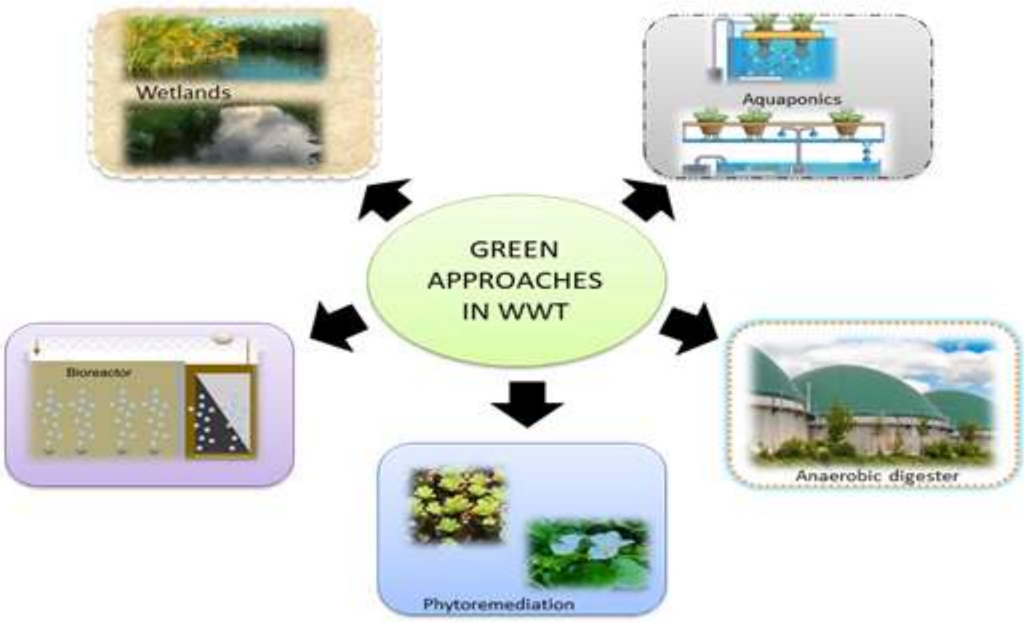

Fig 1: Schematic representation of green approaches to wastewater treatment

Constructed Wetlands: Constructed wetlands: These are artificial wetlands designed to treat wastewater. They use plants to absorb nutrients and pollutants from the water. Constructed wetlands are man-made systems designed to mimic the natural processes of wetlands in order to treat and purify wastewater. In a constructed wetland, wastewater is directed through a series of shallow ponds or channels that are planted with wetland vegetation such as cattails, reeds, or rushes. The plants and associated microorganisms in the wetland work together to break down and remove pollutants from the wastewater (Ravikumar *et al*., 2022; Agaton, and Guila, 2023). The process of wastewater treatment in a constructed wetland is known as phytoremediation, or the use of plants to remove contaminants from soil or water. As wastewater flows through the wetland, the plants and associated microorganisms absorb and metabolize pollutants such as organic matter, nutrients, and heavy metals. In addition, the plants also help to oxygenate the water, promote the growth of beneficial bacteria, and provide a habitat for wildlife (Nedjimi, 2021; Raklami e*t al*., 2022). Constructed wetlands have been shown to be an effective and sustainable method of wastewater treatment, particularly for small communities and rural areas where traditional wastewater treatment methods may be too expensive or impractical. However, the effectiveness of a constructed wetland depends on a number of factors, including the type and amount of pollutants in the wastewater, the design of the wetland, and the maintenance and management of the system over time (Rahman *et al*., 2020; Waly *et al*., 2022).

Phytoremediation: Phytoremediation is a natural treatment system that uses plants to remove contaminants from soil, water, and air. This process is often used to clean up polluted sites, such as former industrial areas, landfills, and mines, and can be an effective and environmentally friendly alternative to traditional remediation methods. Phytoremediation has several advantages over traditional remediation methods. It is typically less expensive, requires less energy, and produces less waste. Additionally, it is often more aesthetically pleasing than traditional remediation methods, as it can involve the use of vegetation to improve the appearance of a site (Adetunji e*t al*., 2023a; Mocek-Płóciniak e*t al*., 2023). However, phytoremediation is not always the best option for every contaminated site. The effectiveness of the process depends on several factors, including the type and extent of contamination, the type of plants used, and the climate and soil conditions of the site. Additionally, phytoremediation can be a slow process and may require long-term monitoring to ensure that contaminants do not re-enter the environment (Babu e*t al*., 2021; Alsafran e*t al*., 2022).

There are several types of phytoremediation systems that can be used depending on the type and extent of contamination. Some of the most common systems include:

Phytoextraction: This process involves using plants to absorb contaminants from the soil, which are then harvested and removed from the site. This method is particularly useful for removing heavy metals, such as lead and arsenic, from contaminated soil (Arjun e*t al*., 2022; Khan e*t al*., 2023; Sharma e*t al*., 2023).

Phytostabilization: In this process, plants are used to immobilize contaminants in the soil, preventing them from leaching into groundwater or being released into the air. This method is often used for sites contaminated with metals, such as mine tailings (Nedjimi, 2021; Shakeel e*t al*., 2022).

Rhizofiltration: This process involves using plants with specialized root systems to remove contaminants from water. The roots of these plants absorb and accumulate pollutants, which are then removed by harvesting the plants (Kafle e*t al*., 2022; Mocek-Płóciniak e*t al*., 2023).

Phytodegradation: This method involves using plants to break down organic pollutants, such as petroleum products, into less harmful compounds. This process is often used for contaminated soil and groundwater (Yan e*t al*., 2020; Verma, 2022).

*Bioreactors***:** Bioreactors: Bioreactors are commonly used in natural treatment systems as a way to improve the treatment efficiency of the system. Natural treatment systems such as constructed wetlands, bioretention cells, and vegetated filter strips rely on natural processes to treat wastewater or stormwater, but the addition of a bioreactor can enhance these processes and lead to better water quality. A bioreactor is a vessel that contains a biologically active environment, typically with a mix of bacteria, fungi, and other microorganisms. Bioreactors can be used to remove contaminants from water by encouraging the growth of microorganisms that break down the pollutants (Sarazen, 2020, Valenca *et al*., 2021). The type of bioreactor used depends on the specific contaminants that need to be removed. There are several types of bioreactors commonly used in natural treatment systems, including:

Subsurface Flow Bioreactors: This type of bioreactor is typically used in constructed wetlands and consists of a bed of gravel or sand where wastewater flows through. The microorganisms attached to the gravel or sand remove contaminants from the wastewater as it passes through (ZeB e*t al*., 2020; Aguado e*t al*., 2022).

Upflow Bioreactors: These bioreactors are similar to subsurface flow bioreactors, but the wastewater flows upwards through the bed of gravel or sand. This allows for better aeration of the microorganisms and can lead to improved treatment efficiency (Narayanan, and Narayan, 2019; Tekere, 2019).

Floating Treatment Wetlands: These bioreactors consist of floating mats or rafts that support plants and microorganisms. The plants provide a surface area for the microorganisms to attach to and remove contaminants from the water (Park e*t al*., 2019; Wei e*t al*., 2020; Arslan e*t al*., 2022).

Vertical Flow Bioreactors: These bioreactors are typically used in stormwater treatment systems and consist of a vertical column filled with a mix of gravel, sand, and organic material. The stormwater flows through the column and is treated as it passes through the biologically active material (Lopez-Ponnada, 2019; Milovanović e*t al*., 2020).

Composting: Composting: This is a natural process that involves breaking down organic matter into a nutrient-rich soil amendment. Composting can be used to treat wastewater by adding organic matter to the wastewater and allowing it to decompose naturally. Composting is the process of breaking down organic matter such as food waste, yard trimmings, and leaves into a nutrient-rich soil amendment called compost (Saraya *et al*., 2020; Mathew *et al*., 2022). Composting is a natural process that can be done at home or on a larger scale in commercial facilities. The composting process involves several stages, starting with the accumulation of organic materials in a pile or bin. The organic matter is then broken down by microorganisms such as bacteria and fungi, which consume the organic material and convert it into a more stable form (Sayara e*t al*., 2020; Mathew e*t al*., 2022). The compost pile needs to be turned regularly to ensure that oxygen is present and to facilitate the breakdown of the organic matter. Composting has several benefits, including reducing the amount of waste sent to landfills, reducing greenhouse gas emissions, and producing a nutrient-rich soil amendment that can be used in gardens and farms. Composting also helps to conserve water and reduce the need for synthetic fertilizers. There are several different methods of composting, including hot composting, cold composting, and vermicomposting (composting with worms). The method used depends on the available space, time, and the amount and type of organic matter being composted (Ayilara *et al.*, 2020; Lee & Khor, 2023). There are many different types of composting systems, including backyard composting bins, worm composting systems, and commercial composting operations. Each system has its own advantages and disadvantages, and the best system for a particular situation will depend on factors such as available space, the types and amount of materials to be composted, and the desired end use of the compost. There are several benefits to composting. First, it reduces the amount of organic waste that goes to landfills, which can help reduce greenhouse gas emissions and conserve landfill space. Second, composting can help improve soil health by adding organic matter and nutrients back into the soil. Finally, composting can be a fun and rewarding activity that can help reduce food waste and promote sustainable living (Ferronato, and Torretta, 2019).

Aquaponics: Aquaponics: This is a system that combines aquaculture (fish farming) and hydroponics (growing plants in water). The fish provide nutrients for the plants, and the plants filter the water for the fish. Aquaponics is a sustainable food production system that combines aquaculture (fish farming) with hydroponics (soil-less plant cultivation). It is a closed-loop system in which the waste produced by fish is used as a nutrient-rich fertilizer for plants, and the plants, in turn, filter the water for the fish (Atique *et al*., 2022; Calone and Orsini, 2022). The basic concept of aquaponics is that fish are raised in tanks, and the water from the tanks is circulated through a system of pipes to plant beds. The plant roots absorb the nutrients from the fish waste, and the filtered water is returned to the fish tanks. This creates a symbiotic relationship between the fish and the plants, with each benefiting from the other. Aquaponics is a highly efficient and sustainable way to grow food, as it requires significantly less water and space than traditional farming methods (Wu *et al*., 2022). Additionally, because the system is closed-loop, there is very little waste or environmental impact. Aquaponics is used to grow a wide variety of crops, including herbs, vegetables, and even fruits. It is also used to raise a variety of fish, including tilapia, trout, and catfish. Aquaponics systems can be set up on a small scale for home use, or on a larger scale for commercial production. These natural treatment systems can be effective in treating green wastewater and can provide an alternative to traditional wastewater treatment methods that rely on chemicals and energy-intensive processes. However, it's important to design and operate these systems properly to ensure they are effective and sustainable (Obirikorang *et al*., 2021; Vasdravanidis *et al*., 2022).

Table 1: Outlining the use of natural treatment systems for green wastewater

Natural Treatment System	Description	Advantages	Disadvantages	Reference
Constructed Wetlands	Wetland system designed to treat wastewater, typically with a gravel bed and planted vegetation	Effective at removing pollutants, low operating costs, aesthetically pleasing	Requires a large footprint, may not be suitable for all climates	Vymazal, 2022; Gabr *et al*., 2023
Biofilters	Soil-based system with a vegetative cover, used to treat runoff or wastewater	Effective at removing pollutants, low cost and maintenance, can be used in a variety of locations	Requires suitable soil and vegetation, may be limited by available space	Xia e*t al*., 2020; Gavrilescu, 2021; Sharma, 2021
Rain Gardens	Landscaped area designed to capture and treat rainwater runoff	Reduces stormwater runoff, provides habitat for wildlife, aesthetically pleasing	May not be suitable for all locations or soil types, requires ongoing maintenance	Chan *et al*., 2019
Phytoremediation	Use of plants to remove contaminants from soil or water	Can be effective at removing pollutants, can be used in a variety of locations	May require a long time to be effective, may not be suitable for all contaminants	Yan e*t al*., 2020; Solomou e*t al*., 2022
Aquatic Plant Systems	Use of aquatic plants to treat wastewater	Can be effective at removing pollutants, can be used in a variety of locations	May require a long time to be effective, may be limited by available space	Sharma, 2021; Bala e*t al*., 2022; Mata e*t al*., 2022;

Energy-Efficient Treatment Technologies of Wastewater: There are several energy-efficient treatment technologies available for wastewater treatment (Table 2). Some of the commonly used technologies are:

Anaerobic Digestion: Anaerobic digestion is an energy-efficient treatment process that involves the breakdown of organic matter in the absence of oxygen by a group of microorganisms called anaerobes. This process produces biogas, which is primarily composed of methane and carbon dioxide, and a nutrient-rich residue called digestate. Biogas can be used to generate electricity and heat, which can reduce the energy requirements of the treatment process (Korbag *et al*., 2021; Harirchi *et al*., 2022). The biogas produced from anaerobic digestion can be used for electricity and heat generation, transportation fuel, or injected into the natural gas grid. This process is considered energy-efficient because it uses organic waste as a feedstock, which would otherwise be sent to landfills or incinerators, and it produces renewable energy that can replace fossil fuels (Alshawaf *et al*., 2021; Abanades *et al*., 2022).

Membrane Bioreactors (MBRS): Membrane Bioreactors (MBRs) are an advanced wastewater treatment process that combines the biological treatment of activated sludge with the separation capabilities of membrane filtration. MBRs have become increasingly popular in recent years due to their energy-efficient nature and ability to produce high-quality effluent. MBRs use a combination of biological processes and membrane filtration to treat wastewater (Bhattacharyya *et al*., 2022). The biological process involves the use of microorganisms to break down organic matter in the wastewater, while the membrane filtration removes suspended solids, bacteria, and other contaminants. One of the main advantages of MBRs is their energy efficiency. Because the process relies on biological activity rather than chemical treatment, it requires less energy than other wastewater treatment methods. Additionally, the membrane filtration process is more efficient than traditional settling methods, which can require large amounts of energy to operate (Al-Asheh *et al*., 2021). Another advantage of MBRs is their ability to produce high-quality effluent. The membrane filtration process removes particles as small as 0.1 microns, resulting in a very clean effluent. This makes MBRs ideal for applications where high-quality effluent is required, such as water reuse or discharge into sensitive environments. Overall, MBRs offer a highly efficient and effective method of wastewater treatment. Their energy efficiency and ability to produce high-quality effluent make them an attractive option for a wide range of applications (Yang *et al*., 2020; Pervez *et al*., 2021).

Sequencing Batch Reactors (SBRS): Sequencing Batch Reactors (SBRs) are a type of activated sludge process that treat wastewater in batches rather than continuously. The process involves filling a reactor with wastewater, aerating the mixture to promote the growth of microorganisms that break down organic matter, and then settling the solids to the bottom of the reactor. Once the solids have settled, the treated water is decanted off the top and discharged. Compared to other treatment processes, SBRs have a relatively low energy demand because they do not require continuous aeration (Shao *et al*., 2022). Instead, aeration is only required during certain stages of the process, such as when the microorganisms are actively breaking down organic matter. Additionally, the batch process allows for more efficient use of energy as the reactor can be turned off when not in use, which reduces energy consumption. Generally, SBRs are a cost-effective and energy-efficient option for treating wastewater, making them a popular choice for both municipal and industrial wastewater treatment facilities (Li *et al*., 2023).

Electrocoagulation (EC): Electrocoagulation (EC) is an electrochemical treatment process that is used to remove contaminants from wastewater. The process involves passing an electrical current through two or more electrodes that are submerged in the wastewater. This results in the formation of coagulants (metal hydroxides) that help to remove contaminants by adsorption, coagulation, and flocculation. EC is considered to be an energy-efficient treatment process because it requires less energy than traditional treatment processes such as activated sludge or chemical coagulation (Gasmi *et al*., 2022; Graça, and Rodrigues, 2022; Boinpally *et al*., 2023). This is because the process does not require the addition of chemicals, and the energy used is mainly for powering the electrodes. Additionally, the process is highly efficient at removing contaminants such as heavy metals, organic compounds, and suspended solids. EC has been found to be effective in treating various types of wastewater, including industrial, agricultural, and domestic wastewater. The process has been used to remove contaminants such as oil and grease, heavy metals, nutrients, and pathogens (Khan *et al*., 2023). Additionally, the process has been found to be effective in reducing the concentration of total suspended solids (TSS): chemical oxygen demand (COD): and biological oxygen demand (BOD). Overall electrocoagulation is a promising wastewater treatment process that has the potential to provide energy-efficient and effective treatment of various types of wastewater. However, it is important to note that the effectiveness of the process depends on various factors such as the type and concentration of contaminants in the wastewater, the design of the system, and the operating conditions (Gali *et al*., 2022; Shabangu *et al*., 2022).

Table 2: Energy-efficient treatment technologies of wastewater

Treatment Technology	**Description of Wastewater**	**Energy Efficiency**	**References**
Aerobic Treatment	Wastewater containing high concentrations of organic matter and nutrients, such as domestic sewage or industrial effluent, is treated by the addition of oxygen and microorganisms that consume the organic matter, producing carbon dioxide and water. This process can be accomplished through different methods, such as activated sludge, trickling filters, or rotating biological contactors.	Moderate to High energy efficiency, as the process requires aeration and mixing, which can be energy-intensive. However energy can be recovered from the biogas produced during treatment.	Ghimire *et al.*, 2021; Wen *et al.*, 2021
Anaerobic Treatment	Similar to aerobic treatment, but without the addition of oxygen. The organic matter is decomposed by bacteria in an oxygen-free environment, producing biogas (a mixture of methane and carbon dioxide) and a nutrient-rich effluent. This technology is particularly suitable for high-strength industrial wastewater or sludge treatment.	High energy efficiency, as the process produces biogas that can be used for energy generation, offsetting energy requirements for treatment.	Köksal e*t al*., 2018; Kiselev e*t al*., 2021
Membrane Filtration	Wastewater is passed through a membrane that allows the separation of solids, dissolved solids, and bacteria from the water. This technology can be used for a variety of wastewater types, such as municipal or industrial wastewater, and can produce high-quality effluent for reuse or discharge.	Moderate to High energy efficiency, depending on the type of membrane used and the pressure required for filtration. Energy can be recovered from the concentrate or backwash streams.	Maaz e*t al*., 2019; Zielińska, and Ojo, 2023.
Reverse Osmosis	This technology uses pressure to force water through a semipermeable membrane, removing dissolved salts and other contaminants from the water. It is typically used for brackish or seawater desalination and can produce high-quality water for reuse or discharge.	Low to Moderate energy efficiency, as the process requires high pressure to overcome the osmotic pressure of the feed water. Energy recovery can be achieved through the use of energy recovery devices or the integration of the process with other treatment technologies.	di Biase e*t al*., 2019; Wang e*t al*., 2020; Alharthi e*t al*., 2023; Gopalakrishnan e*t al*., 2023; JacoB; *et al*., 2023
Ultraviolet (UV) Disinfection	Wastewater is exposed to UV light, which damages the DNA of microorganisms, rendering them unable to reproduce. This technology can be used as a final treatment step to disinfect wastewater prior to discharge or reuse.	High energy efficiency, as the process requires minimal energy input and does not require the use of chemicals.	Ren e*t al*., 2021
Chemical Treatment	Chemicals, such as coagulants and flocculants, are added to wastewater to remove suspended solids, metals, and other contaminants. This technology is often used in conjunction with other treatment methods, such as aerobic or anaerobic treatment, to improve effluent quality.	Low to Moderate energy efficiency, as the process requires the use of chemicals and may require additional energy input for mixing or dosing.	Tian e*t al*., 2021; Huang e*t al*., 2022; Yi e*t al*., 2022; Cerrillo e*t al*., 2023
Electrochemical Treatment	This technology uses an electric current to oxidize or reduce pollutants in wastewater, producing harmless byproducts. It can be used for a variety of wastewater types, including industrial wastewater and landfill leachate.	Moderate to High energy efficiency, depending on the type of electrochemical cell used and the nature of the pollutants. Energy can be recovered from the byproducts produced during treatment.	Ghernaout, and Elboughdiri, 2020
Constructed Wetlands	Wastewater is treated by passing it through a wetland system, which consists of a shallow basin filled with soil, gravel, and wetland vegetation. The wetland plants and microorganisms remove nutrients and pollutants from the water, producing a high-quality effluent. This technology is particularly suitable for small-scale wastewater treatment and decentralized systems.	High energy efficiency, as the process relies on natural processes and does	Oscar, and Caren, 2021; Wang e*t al*., 2022

Water Reuse Treatment Technologies of Wastewater: Reusing water is a practice that is highly desired globally, mostly utilized for the preservation of ecosystems, reduction of the consumption of potable water supplies, and conservation of water resources. Water reuse is now possible with a wide range of efficient methods, mostly as an advanced treatment step in wastewater treatment facilities. These technologies, which are based on biological, chemical, mechanical, and natural processes, differ in their features. But, while choosing the best technical advancement for every water reuse application, one should consider the benefits and drawbacks of each technique (Santos *et al.*, 2023). There are several technologies available for treating wastewater and reusing it for various purposes. Some of the commonly used water reuse treatment technologies are:

Reverse Osmosis (RO): Reverse osmosis (RO) is a water treatment process that uses a semi-permeable membrane to remove dissolved solids, organic molecules, and other contaminants from water. RO is an effective technology for water reuse treatment because it can remove a wide range of pollutants and produce high-quality water that can be used for a variety of applications, including irrigation, industrial processes, and even drinking water. In water reuse applications, RO is typically used as a final polishing step after other treatment processes, such as sedimentation, filtration, and disinfection, have been used to remove larger particles and microorganisms. This allows the RO membrane to operate more efficiently and extend its lifespan. During the RO process, water is forced through a semi-permeable membrane under high pressure (Obotey, and Rathilal, 2020). The membrane has pores that are small enough to block the passage of dissolved salts, minerals, and other contaminants, but large enough to allow water molecules to pass through. The purified water that passes through the membrane is collected in a permeate stream, while the concentrated wastewater containing the rejected contaminants is sent to a disposal system. One of the main advantages of RO for water reuse treatment is its ability to remove a wide range of contaminants, including salts, minerals, and organic compounds. This makes it a versatile technology that can be used for a variety of applications, from producing high-quality irrigation water for agriculture to providing purified water for industrial processes and even drinking water (Gul *et al*., 2021). However, RO is also an energy-intensive process that requires significant amounts of electricity to operate the high-pressure pumps that are used to force water through the membrane. This can make it expensive to implement on a large scale especially in areas with limited access to affordable energy sources. Overall, RO is a highly effective technology for water reuse treatment, but it should be used in combination with other treatment processes to ensure the highest level of water quality and to minimize energy consumption and costs (Do-Thi e*t al*., 2021).

Ultraviolet (UV) Disinfection: Ultraviolet (UV) Disinfection: UV disinfection is a common method used in water reuse treatment to eliminate harmful microorganisms and pathogens that may still be present in the treated water. UV disinfection involves exposing the water to a specific wavelength of ultraviolet light that is harmful to bacteria, viruses, and other microorganisms. UV disinfection is particularly effective in water reuse treatment because it does not require the addition of chemicals, and it does not produce harmful byproducts like some chemical disinfection methods. UV disinfection is also relatively easy to implement and maintain, making it a popular choice for water reuse treatment (khan *et al*., 2022). However, UV disinfection does have some limitations. For example, it may not be effective in treating all types of microorganisms, and it may not be able to eliminate some chemicals or other contaminants that may be present in the water. Additionally, UV disinfection requires a certain level of energy to operate, which can be costly in some cases. Overall, UV disinfection can be an effective method for ensuring the safety and quality of water in reuse treatment applications. However, it is important to consider the specific requirements of the application and the limitations of the method before implementing it (Collivignarelli *et al*. 2020).

Ozonation: Ozonation is a widely used process in water treatment, including water reuse treatment. It involves the use of ozone, a powerful oxidizing agent, to remove organic and inorganic contaminants from water. In water reuse treatment, ozonation can be used as a pretreatment step to remove contaminants that may not be effectively removed by other treatment processes such as biological treatment or filtration. It can also be used as a final step in the treatment process to further disinfect the water and remove any remaining organic compounds. One of the main advantages of ozonation is its ability to effectively remove a wide range of contaminants, including microorganisms, organic and inorganic compounds, and taste and odor-causing compounds (Zahmatkesh *et al*., 2022). Ozonation can also be used to control algae growth in water storage tanks and distribution systems. However, ozonation has some limitations, including its high cost compared to other treatment processes and the production of potentially harmful byproducts such as bromate. Therefore, it is important to carefully evaluate the benefits and drawbacks of ozonation and to consider other treatment options when designing a water reuse treatment system (Psaltou and Zouboulis, 2020).

Activated Carbon Filtration: Activated carbon filtration is an effective method for treating water for reuse purposes. Activated carbon is a highly porous material with a large surface area, which makes it an ideal material for adsorbing organic and inorganic contaminants from water. In the context of water reuse, activated carbon filtration can be used as a tertiary treatment step to remove any remaining organic and inorganic contaminants that were not removed during the primary and secondary treatment steps. Activated carbon filtration works by passing water through a bed of activated carbon, which adsorbs contaminants from the water. The contaminants are attracted to the surface of the activated carbon, where they are trapped and held (Muttil *et al*., 2022). Over time, the activated carbon becomes saturated with contaminants and needs to be replaced or regenerated. There are two main types of activated carbon filtration systems: granular activated carbon (GAC) and powdered activated carbon (PAC). GAC systems consist of a bed of activated carbon particles that range in size from 0.2 to 5 millimeters. PAC systems use smaller particles of activated carbon, typically less than 0.15 millimeters in size, which are mixed with the water to form a slurry. Both GAC and PAC systems have advantages and disadvantages. GAC systems are more commonly used for large-scale water treatment applications because they have a longer lifespan and are easier to maintain. PAC systems are typically used for smaller-scale applications or for treating water that has a high concentration of contaminants. Overall, activated carbon filtration is a highly effective method for treating water for reuse purposes, and it is an important component of many water reuse treatment processes (Pillai, 2020).

Chlorination: Chlorination is a commonly used disinfection process in water treatment to kill harmful microorganisms such as bacteria, viruses, and parasites. It involves adding chlorine, usually in the form of chlorine gas or sodium hypochlorite, to water to create a disinfectant that eliminates or reduces the presence of pathogenic microorganisms. Water reuse treatment refers to the process of treating wastewater to make it safe and suitable for reuse. The treatment typically involves multiple steps, including physical, biological, and chemical treatment processes to remove contaminants and pathogens from the wastewater. Chlorination is often used as part of the water reuse treatment process to disinfect the treated wastewater before it is reused for non-potable purposes such as irrigation, industrial processes, and toilet flushing (Inobeme *et al*., 2023b). The level of chlorine added to the treated water is carefully controlled to ensure that it is effective in killing harmful microorganisms while minimizing any potential health risks associated with the disinfection byproducts. It is important to note that while chlorination is an effective disinfection method, it may not be effective in removing all types of contaminants, such as chemicals or heavy metals. Therefore, it is often used in combination with other treatment processes such as filtration, reverse osmosis, and activated carbon adsorption to ensure the water is safe for reuse (Kesar, and Bhatti, 2022).

*Onsite Treatment Technologies of Wastewater***:** Onsite treatment of wastewater, also known as decentralized wastewater treatment, refers to the treatment of wastewater at or near the location where it is generated, rather than transporting it to a centralized treatment facility. This approach is commonly used in rural areas, small communities, and individual households that are not connected to a centralized sewer system. Onsite treatment systems typically consist of a septic tank and a drainfield (Capodaglio, 2017). The septic tank is a large, watertight container that receives the wastewater from the home or business. The tank separates the solids from the liquids and allows the solids to settle to the bottom, forming a layer of sludge. The liquid effluent then flows out of the tank and into the drainfield. The drainfield is a network of pipes buried in trenches filled with gravel or other permeable material. The effluent from the septic tank flows into the drainfield, where it is filtered and treated by naturally occurring bacteria in the soil. The treated effluent then percolates into the groundwater or is taken up by plants. Onsite treatment systems require regular maintenance to ensure they function properly. This includes pumping out the septic tank every few years to remove the accumulated sludge, and avoiding the use of harsh chemicals that can harm the bacteria in the tank and soil (Table 3**)** (Wang *et al*., 2021).

There are several types of onsite wastewater treatment systems, including septic systems, aerobic treatment units, and constructed wetlands. The type of system used depends on factors such as the volume and quality of the wastewater, the soil type and depth, and the local regulations.

Septic systems: Septic systems are the most common type of onsite treatment system and consist of a septic tank and a drain field. Wastewater from the house is collected in the septic tank, where solids settle and are broken down by bacteria. The liquid wastewater then flows to the drain field, where it percolates through the soil and is further treated by natural processes. Onsite treatment of wastewater can be an effective way to manage wastewater in rural or remote areas where centralized treatment facilities are not available or practical. However, it is important to ensure that the system is designed, installed, and maintained properly to ensure effective treatment and prevent contamination of groundwater and surface water (Cavalheri e*t al*., 2022). Regular maintenance of a septic system is important to ensure its proper functioning and longevity. This includes having the septic tank pumped every 3-5 years, avoiding the disposal of harmful substances such as chemicals and non-biodegradable materials, and being mindful of water usage to prevent overloading the system. A failing septic system can lead to costly repairs environmental damage, and health hazards. It's important to note that the type of septic system that is best for your property will depend on a variety of factors, including the size and location of your property, the soil conditions, and local regulations. There are several types of septic systems each designed to meet the needs of different types of properties and soil conditions. Here are some of the most common types of septic systems (Knisz *et al*., 2021). Conventional septic system: This is the most common type of septic system, which includes a septic tank and a drain field. Wastewater from the home flows into the septic tank, where solids settle to the bottom and are broken down by bacteria. The liquid wastewater then flows into the drain field, where it is filtered through layers of soil. Chamber septic system: This type of system is similar to a conventional septic system, but it uses plastic chambers instead of a traditional drain field. The chambers allow for better oxygen flow, which promotes the growth of bacteria that break down the wastewater more efficiently (Cavalheri e*t al*., 2022). Mound septic system: This type of system is used when the soil is not suitable for a conventional septic system. A mound of sand and gravel is built above the natural soil, and the septic tank and drain field are placed on top of the mound. The wastewater is filtered through the sand and gravel before entering the natural soil. Aerobic treatment unit (ATU) system: This type of system uses oxygen to promote the growth of bacteria that break down the wastewater more efficiently than a conventional septic system. The system includes a septic tank and an aerator, which pumps oxygen into the tank to promote bacterial growth. The treated wastewater is then filtered through a drain field or other filtration system. This method has the advantage of being able to be utilized in homes with smaller lots, in places with poor soil conditions, in areas with an excessively high water table, or in residences near surface water bodies that are vulnerable to nutrient contamination from wastewater effluent. For ATUs, regular lifetime maintenance should be anticipated (Knisz *et al*., 2021). Drip irrigation septic system: This type of system is similar to a conventional septic system, but it uses a series of small tubes to distribute the wastewater to a drain field. The tubes allow for a more even distribution of the wastewater, which can be beneficial in areas with poor soil conditions (Cavalheri e*t al*., 2022).

Table 3: some common onsite treatment technologies for wastewater

Onsite Treatment Technology	Description	References
Septic tank	A watertight tank that receives wastewater from a building's plumbing system. Solids settle to the bottom and are broken down by bacteria. Effluent is discharged to a drainfield for further treatment.	Hassan e*t al*., 2021
Aerobic treatment unit	A tank that uses oxygen to promote the growth of aerobic bacteria, which break down organic matter. Treated effluent can be discharged to a drainfield or used for irrigation.	Englande e*t al*., 2015; Schaider e*t al*., 2017
Mound system	A drainfield placed above the natural soil surface, with a sand or gravel fill layer to treat effluent. Soil beneath the mound provides further treatment.	Shahid e*t al*., 2020
Constructed wetland	A series of lined ponds planted with wetland vegetation. Wastewater flows through the ponds, where plants and microorganisms remove nutrients and other contaminants.	Opitz e*t al*., 2021
Recirculating sand filter	A filter bed filled with sand and gravel that treats wastewater. Effluent is recirculated to enhance treatment.	Dacewicz, and Chmielowski, 2018; Al-Ajalin e*t al*., 2020
Drip irrigation	Effluent is distributed through a series of small, low-volume emitters in a drip irrigation system. Soil provides further treatment as effluent percolates downward.	Abou-Seeda e*t al*., 2020; Dirwai e*t al*., 2021

Limitation of Septic Systems: Septic systems have some limitations that homeowners should be aware of, including:

Maintenance requirements: Septic systems require regular maintenance, including pumping of the tank every 3-5 years, to ensure they function properly. Neglecting maintenance can lead to clogging, backups, and other issues (Hoghooghi *et al*., 2021). Limited capacity: Septic systems have a limited capacity for handling wastewater. If the system is overloaded with too much water or waste, it can lead to system failure and the need for costly repairs (Hughes *et al*., 2021). Environmental concerns: Improperly maintained or malfunctioning septic systems can release harmful pollutants into the environment, including bacteria, viruses, and chemicals. This can pose a health risk to people and animals in the surrounding area (Lorenzo *et al*., 2018). Restrictions on land use: In some areas, there may be restrictions on the use of septic systems, such as limitations on the size of the property or the type of soil (Hoghooghi *et al*., 2021). Upfront costs: While septic systems can be cost-effective in the long run, the upfront costs of installation can be relatively high especially for larger systems or properties with difficult soil conditions (Hughes *et al*., 2021).

Advantages of Septic systems: Septic systems have several advantages:
Cost-effective: Septic systems are generally less expensive to install and maintain than centralized sewer systems. Once installed, they do not require monthly fees or bills for water treatment (Hoghooghi *et al*., 2021).
Self-sufficient: Septic systems are self-contained and do not require connection to a centralized sewer system. This makes them a good option for rural areas or places where a centralized sewer system is not available (Brzusek e*t al*., 2022).
Environmentally friendly: Septic systems can be designed to treat wastewater on-site, which can reduce the amount of pollutants that are released into the environment. When properly maintained, they can also help protect groundwater and nearby bodies of water (Capps e*t al*., 2020; Mathew e*t al*., 2023a).
Flexibility: Septic systems can be designed to fit a variety of properties and soil types. This means that they can be customized to meet the specific needs of individual homes and properties (Chen e*t al*., 2023).
Long lifespan: Septic systems are durable and can last for many years with proper maintenance. This can make them a good long-term investment for homeowners (Hussein and Mona, 2018).

Aerobic treatment units: Aerobic treatment units use bacteria and oxygen to break down organic matter in the wastewater. The treated effluent can then be discharged into the soil or surface water. These units are typically used in areas where conventional septic systems are not feasible due to soil or site conditions. ATUs are designed to treat wastewater more thoroughly than conventional septic systems, producing effluent that is cleaner and safer for the environment. The aerobic process used in ATUs involves the use of aerobic bacteria that require oxygen to break down and digest organic matter in the wastewater (Adegoke and Stenstrom, 2019). The process takes place in a tank or chamber that is specially designed to provide aeration and mixing to promote the growth of these bacteria. As the wastewater flows through the ATU, it is exposed to the aerobic bacteria, which break down the organic matter and convert it into carbon dioxide, water, and other harmless substances. The effluent that is produced is then discharged into the environment, usually into a drain field or other treatment system. ATUs are generally more expensive to install and maintain than conventional septic systems, but they can be more effective in treating wastewater and are often required in areas where conventional systems are not permitted. There are different types of aerobic treatment units, including activated sludge systems, fixed-film systems, and rotating biological contactors. The specific type used depends on factors such as the size of the treatment system, the quality of the wastewater, and the amount of organic matter present. ATUs are typically more effective at treating wastewater than traditional septic systems, and they can be a good option for areas where there is no access to municipal wastewater treatment facilities. However, they require regular maintenance and monitoring to ensure they are functioning properly and to prevent any potential environmental or health hazards (Majumder e*t al*., 2021; Inobeme e*t al*., 2023a).

Limitation of Aerobic Treatment Units: While ATUs can be effective in treating wastewater, there are several limitations to their use. Some of the key limitations include:
Energy consumption: ATUs require energy to operate, as they need a continuous supply of air to maintain aerobic conditions. This can result in higher electricity bills for the homeowner or business operating the system (Hyde *et al*., 2019).
Maintenance requirements: ATUs require regular maintenance to keep them operating effectively. This includes tasks such as cleaning filters, replacing worn-out parts, and monitoring the system for signs of wear and tear.
Climate limitations: ATUs may not be suitable for use in areas with cold or freezing temperatures, as the wastewater may freeze and damage the system. Similarly, hot and dry conditions can cause the system to dry out and become less effective (Hyde *et al*., 2019).
Nitrogen removal limitations: ATUs may not be effective at removing nitrogen from wastewater, which can lead to environmental problems if the treated wastewater is discharged into waterways (Adegoke and Stenstrom, 2019).
Space limitations: ATUs require a relatively large amount of space compared to other types of wastewater treatment systems. This can make them unsuitable for use in small or densely populated areas where space is limited (Majumder e*t al*., 2021).

Advantages of Aerobic Treatment Units: Aerobic Treatment Units (ATUs) offer several advantages over

other types of wastewater treatment systems, including:
High treatment efficiency: ATUs are highly effective in treating wastewater, removing up to 90% of pollutants, including organic matter and nutrients, from the wastewater (Majumder e*t al*., 2021).
Smaller footprint: ATUs are typically smaller in size than conventional wastewater treatment systems, making them ideal for areas with limited space (Sathya e*t al*., 2022).
Low odor and noise levels: ATUs produce little to no odor and noise, making them a preferred option for residential areas (Ahmed e*t al*., 2022).
Low energy consumption: ATUs require less energy to operate than other types of treatment systems, such as activated sludge systems, due to the use of natural aeration (Ng e*t al*., 2022).
Flexible design: ATUs can be designed to accommodate a variety of wastewater flows, making them suitable for a wide range of applications (Obaideen e*t al*., 2022).
Minimal sludge production: ATUs produce minimal amounts of sludge, reducing the need for disposal and associated costs (Kwaku-Armah e*t al*., 2020).
Easy to maintain: ATUs are relatively easy to maintain, with simple mechanical components and easy access for inspection and cleaning.

Constructed Wetlands: Constructed wetlands use plants and microorganisms to treat wastewater. The wastewater flows through a series of shallow, planted basins, where the plants and microorganisms remove nutrients and pollutants. Constructed wetlands are a type of wastewater treatment system that use natural processes to remove pollutants from water. They are designed to mimic the natural processes that occur in wetlands, such as the uptake of nutrients by plants and the breakdown of organic matter by microorganisms. In a constructed wetland, wastewater is first treated to remove large particles and solids before being directed into a bed of gravel or soil. The bed is then planted with a variety of wetland plants, such as cattails, reeds, and rushes, which help to absorb and filter out pollutants (Achak e*t al*. 2023). As the water flows through the bed, it comes into contact with the plants' roots and the microorganisms that live in the soil, which break down organic matter and convert nutrients like nitrogen and phosphorus into forms that are less harmful to the environment. Constructed wetlands can be designed for a variety of applications, from small-scale residential systems to large-scale municipal wastewater treatment plants. They are particularly well-suited for onsite treatment of wastewater in rural areas or other locations where conventional treatment methods are not feasible or cost-effective. One of the benefits of constructed wetlands is that they are relatively low-maintenance compared to other wastewater treatment systems. The plants and microorganisms in the system are self-regulating and require little intervention beyond periodic monitoring and maintenance of the plants themselves (Mathew e*t al*., 2022).

Additionally, constructed wetlands can be designed to blend in with the natural landscape, providing a visually appealing and ecologically valuable addition to the site. While constructed wetlands can be an effective and sustainable way to treat wastewater, it is important to note that they may not be appropriate for all situations. Factors such as soil type, climate, and the characteristics of the wastewater being treated can all affect the effectiveness of the system. As with any wastewater treatment system, careful design and ongoing monitoring and maintenance are critical to ensuring the system's long-term effectiveness (Chakraborti, and Bays, 2023).

Limitation of Constructed Wetlands: Constructed wetlands are an effective and eco-friendly method of treating wastewater and improving water quality. However, like any technology, they have limitations. Here are some of the limitations of constructed wetlands:
Climate-dependent: Constructed wetlands are highly dependent on climatic conditions such as temperature, precipitation, and evaporation. In colder climates, they may freeze in winter, making them less effective at treating wastewater (Singh e*t al*., 2022).
Space requirements: Constructed wetlands require a considerable amount of land, making them less practical in densely populated areas (Hassan e*t al*., 2021).
Initial cost: Constructed wetlands can be expensive to construct and maintain, making them less economically feasible in certain situations (Thalla e*t al*., 2019; Makopondo e*t al*., 2020).
Nutrient limitations: While constructed wetlands are effective at removing nutrients such as nitrogen and phosphorus, they may not be able to remove all nutrients in some situations, such as in areas with high nutrient loads (Gordon e*t al*., 2020).
Maintenance requirements: Constructed wetlands require ongoing maintenance to ensure that they are functioning properly. Maintenance can be time-consuming and costly (Gabr e*t al*., 2023).
Limited pollutant removal: Constructed wetlands are effective at removing certain pollutants such as organic matter and nutrients but may not be as effective at removing other pollutants such as heavy metals and some chemicals (Fu *et al*., 2022; Inobeme e*t al*., 2022).

Advantages of Constructed Wetlands: Cost-effectiveness: Constructed wetlands are generally more cost-effective than traditional treatment methods, such as activated sludge systems or chemical treatments. They require less energy, chemicals, and maintenance, which results in lower operating costs (Nuamah e*t al*., (2020); Rahman *et al.*, 2020).

Sustainability: Constructed wetlands are a sustainable solution for wastewater treatment as they do not produce any harmful byproducts, unlike some traditional treatment methods. The plants and bacteria in the wetland system naturally break down the pollutants in the water, making it safe for release back into the environment (Tuttolomondo *et al.*, 2020; Bai e*t al*., 2022; Berego e*t al*., 2022).

Aesthetics: Constructed wetlands can be designed to blend in with the surrounding landscape, creating a beautiful and natural-looking environment. They can also serve as a habitat for wildlife, increasing biodiversity (Zhang e*t al*., 2020).

Flexibility: Constructed wetlands can be designed to treat different types of water, including stormwater, agricultural runoff, and industrial wastewater. They can also be scaled up or down depending on the volume of water that needs to be treated (García e*t al*., 2020; Vymazal, 2022; Adetunji e*t al*., 2023b).

Resilience: Constructed wetlands are highly resilient and can continue to function even under extreme weather conditions such as floods or droughts. The plants and bacteria in the system can adapt to changes in the environment and continue to effectively treat the water (Stefanakis, 2019; Wilby, 2020; Salimi e*t al*., 2021).

Green Infrastructure Technologies of Wastewater: Green infrastructure technologies for wastewater refer to the use of natural or ecological systems to treat, store, and manage wastewater. These systems can help reduce the strain on conventional wastewater treatment plants and provide a more sustainable and cost-effective approach to managing wastewater. Overall, green infrastructure technologies for wastewater provide an innovative approach to sustainable water management, promoting the use of natural systems to enhance the quality of water and reduce the demand for conventional water treatment methods.

Here are some examples of green infrastructure technologies for wastewater:

Constructed Wetlands

Constructed Wetlands: These are engineered systems that use natural processes to remove pollutants from wastewater. Wetlands consist of shallow ponds or channels filled with aquatic plants that absorb nutrients and filter out contaminants. They are an effective way to treat wastewater and improve water quality.

Green Roofs

Green Roofs: A green roof is a layer of vegetation installed on a roof surface that helps to absorb and filter rainwater. By slowing down the flow of stormwater, green roofs reduce the volume of runoff, which can help prevent flooding and erosion. They also provide insulation, reduce the urban heat island effect, and improve air quality.

Bioretention

Bioretention: Bioretention is a process in which stormwater runoff is filtered through a layer of soil and plants before entering a stormwater management system. This technique is useful in removing pollutants such as heavy metals and nutrients from the stormwater.

Permeable Pavement

Permeable Pavement: Permeable pavement is a type of pavement that allows rainwater to seep through the surface and into the ground. This approach helps to reduce stormwater runoff, which can cause erosion and flooding. Permeable pavement is often used in parking lots, sidewalks, and other outdoor spaces.

Greywater Systems

Greywater Systems: Greywater is wastewater generated from sources other than toilets, such as sinks, showers, and washing machines. Greywater systems capture and treat this water for reuse in irrigation or toilet flushing, reducing demand on freshwater resources.

Nutrient Recovery Treatment of Wastewater: Nutrient recovery is a process that involves the removal and conversion of nutrients such as nitrogen and phosphorus from wastewater to produce useful products such as fertilizers. The traditional wastewater treatment process typically involves the removal of organic matter and nutrients from wastewater before discharging the treated water into the environment. However, this process can lead to the loss of valuable nutrients, which can contribute to environmental problems such as eutrophication (Theregowda *et al*., 2019). Once the nutrients have been recovered, they can be converted into useful products such as fertilizers, which can be used in agriculture to improve crop yields. This process not only helps to reduce the environmental impact of wastewater treatment but also provides a valuable source of nutrients for agriculture, reducing the need for synthetic fertilizers (Di Costanzo *et al*., 2021; Adetunji e*t al*., 2023c).

Nutrient recovery treatment of wastewater involves several steps, including (Figure 2):

Pre-Treatment: Pre-treatment: The wastewater is first screened to remove large solids and then passed through grit chambers to remove grit and sand. Sludge production and handling in wastewater treatment facilities is a serious environmental problem. Anaerobic and aerobic digestion are the main biological stabilization techniques used to treat sludge, which is a complicated substance. The effectiveness of these activities is, however, significantly hampered by the presence of complex organics, microbial flocs extracellular polymeric materials, and other inhibitory chemicals. The literature suggests a variety of pretreatment strategies that can be applied either alone or in combination to mitigate the impact of these rate-limiting issues (Koul *et al*., 2022). This review explains the anaerobic and aerobic digestion of sludge and identifies the problems limiting the process's efficiency. The possible application of pretreatment techniques, such as ultrasonic, thermal, Fenton, microwave, photocatalysis, wet oxidation, and others, is emphasized. The potential for sludge disintegration and solubilization under various situations (such as operating conditions and sludge makeup) varies according to these pretreatment procedures. The ultimate objective is to enhance sludge's biological treatment that comes after. Thermal, ultrasonic, and microwave procedures can effectively dissolve sludge components and break down microbial floc cell walls in a little amount of time (Mitraka *et al*., 2022). However, problems with excessive energy consumption make these procedures unfeasible for field use. Bioleaching or ultrasonography can be used in conjunction with the Fenton process. With less energy required, visible-photocatalysis pretreatment for sludge can enhance anaerobic sludge treatment and biogas production (Kazimierowicz *et al*., 2023).

Primary Treatment: Primary treatment: The wastewater is then passed through sedimentation tanks where the heavier solids settle to the bottom and are removed as sludge. The primary treatment of wastewater involves the physical removal of solid materials and organic matter through a series of processes. The goal of primary treatment is to remove as much of the suspended and settleable solids as possible before the wastewater undergoes further treatment processes. The primary treatment process typically involves the following steps: Screening: The wastewater is passed through screens to remove large objects such as sticks, rags, and plastic debris. Grit Removal: The wastewater is then sent to grit chambers where sand, gravel, and other heavy materials settle to the bottom (Kolsovska, 2022). Sedimentation: The wastewater flows into large sedimentation tanks, where the solids settle to the bottom and are removed as sludge. The clear water at the top of the tank is sent for further treatment (Koul *et al*., 2022). Floatation: This process removes grease, oil, and other floating materials that are difficult to remove by sedimentation. The wastewater is introduced with chemicals that cause these materials to float and be skimmed off the surface (Adetunji, and Olaniran, 2021).

*Secondary Treatment***:** Secondary treatment of wastewater is the second stage of the wastewater treatment process, following primary treatment. The goal of secondary treatment is to further purify the wastewater by removing dissolved and suspended organic matter and nutrients, such as nitrogen and phosphorus that can cause water pollution and harm to the environment. Secondary treatment typically involves biological processes that use bacteria, fungi, and other microorganisms to break down organic matter and convert it into more stable and less harmful substances. The two most common types of secondary treatment are activated sludge process and trickling filter process. In the activated sludge process, the wastewater is mixed with a large population of microorganisms in a large tank or basin called an aeration tank (Ahmed e*t al*., 2022). The microorganisms break down the organic matter, converting it into carbon dioxide, water, and new bacterial cells. The mixture is then sent to a secondary clarifier where the microorganisms are separated from the treated water and either returned to the aeration tank or sent to further treatment or disposal. In the trickling filter process, wastewater is distributed over a bed of rock or other media that supports a thin layer of microorganisms. As the wastewater trickles through the media, the microorganisms remove organic matter and nutrients. The treated wastewater is then sent to a secondary clarifier for separation from the microorganisms and further treatment or disposal (Koul *et al*., 2022).

Tertiary Treatment: Tertiary treatment: In this stage, the wastewater undergoes further treatment to remove any remaining contaminants and nutrients. The primary goal of tertiary treatment is to further purify the wastewater that has already gone through primary and secondary treatment, so it is safe to discharge into the environment or reused. This can include processes such as filtration, disinfection, and chemical treatment (Islam *et al*., 2021).

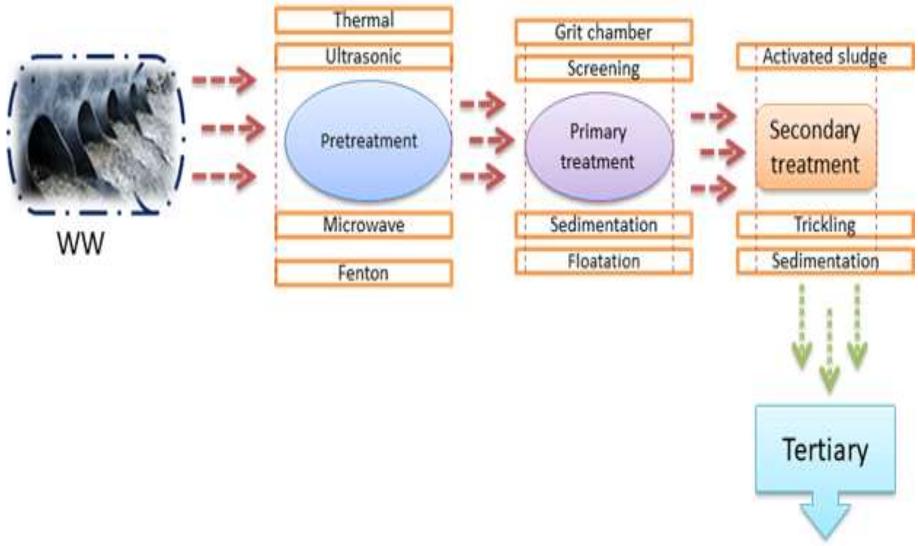

Fig 2: Steps in wastewater treatment

Nutrient Recovery: Nutrient recovery from wastewater refers to the process of removing and capturing nutrients such as nitrogen and phosphorus from wastewater streams for reuse as fertilizer or other applications. This helps to reduce the environmental impact of wastewater discharge and promotes a more sustainable approach to resource management. After the tertiary treatment, the nutrient-rich wastewater is processed to recover the valuable nutrients such as nitrogen and phosphorus (Robles et al., 2020). This can be achieved through various methods, including biological nutrient removal, struvite precipitation, chemical precipitation, and membrane filtration. Nutrient recovery from wastewater has several benefits, including reducing nutrient pollution in water bodies, reducing the demand for synthetic fertilizers, and promoting sustainable resource management. However, it can also be expensive and requires careful management to avoid contamination and ensure the safety of the recovered nutrients (Theregowda e*t al*., 2019; Sniatala e*t al*., 2023).

Technologies Used For Treating Wastewater: There are several technologies used for treating wastewater to make it suitable for reuse. Some of the most common ones include:

Membrane Filtration: This technology involves the use of a membrane to filter out impurities in the wastewater. Membrane filtration is a separation process that uses a semi-permeable membrane to separate particles, impurities, and other unwanted substances from a fluid. The membrane acts as a barrier that allows the fluid to pass through while retaining the particles and other substances. The membrane can be made from a variety of materials such as polymers, ceramics, or metals, and the size of the pores in the membrane can be controlled to allow specific sizes of particles to pass through (Talukder e*t al*., 2022). Membrane filtration can be used in a variety of applications such as water treatment, food and beverage processing, pharmaceuticals, and biotechnology. In water treatment, membrane filtration can remove bacteria, viruses, and other contaminants from drinking water. In the food and beverage industry, it can be used to clarify and concentrate liquids such as fruit juice or milk. In the pharmaceutical and biotechnology industries, it can be used for the separation and purification of proteins and other biomolecules (Obotey and Rathilal, 2020; Anekwe e*t al*., 2022; Hu, and Wu, 2023).

There are several types of membrane filtration, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Microfiltration membranes have larger pore sizes and are used for the removal of suspended solids and bacteria. Ultrafiltration membranes have smaller pore sizes and can remove viruses, proteins, and other molecules. Nanofiltration membranes have even smaller pore sizes and can remove divalent ions, such as calcium and magnesium, and some organic molecules. Reverse osmosis membranes have the smallest pore sizes and can remove ions, including salts and other dissolved solids. Overall, membrane filtration is a versatile and effective separation process with a wide range of applications in various industries (Nasir e*t al*., 2022; Razali e*t al*., 2023).

Biological Treatment: This involves the use of microorganisms to break down organic matter in the wastewater. The most commonly used methods include activated sludge, trickling filters, and sequencing batch reactors. There are several types of biological treatment processes used in wastewater treatment, including activated sludge process, trickling filters, and sequencing batch reactors. These processes rely on different types of microorganisms and different conditions to effectively treat the wastewater. In the activated sludge process, wastewater is mixed with a population of microorganisms in an aeration tank. The microorganisms use oxygen to break down the organic matter and pollutants present in the wastewater (Fito e*t al*., 2019; Liang e*t al*., 2021). After this, the mixture is settled in a clarifier to separate the treated water from the sludge that contains the microorganisms. Trickling filters are another type of biological treatment process, which involve the use of a bed of rock or plastic media through which wastewater flows. Microorganisms grow on the surface of the media, and they use the organic matter and pollutants in the wastewater as a food source. As the wastewater trickles through the media, it is treated by the microorganisms. Sequencing batch reactors involve filling and emptying a tank with wastewater and a population of microorganisms. The microorganisms use the organic matter and pollutants in the wastewater during the fill period, and then the treated water is separated from the sludge during the settling period (Ghaly e*t al*., 2021). Generally, biological treatment is an effective and commonly used method for treating wastewater. It is a cost-effective and environmentally friendly solution, but it requires careful management to ensure that the microorganisms are healthy and effective in treating the wastewater (Mathew *et al*., 2023b; Mathew *et al*., 2023c).

Chemical Treatment: This involves the use of chemicals such as chlorine, ozone, or UV radiation to disinfect the wastewater and remove impurities. There are several types of chemical treatment methods used in wastewater treatment, including coagulation, flocculation, and sedimentation, disinfection, and pH adjustment. Coagulation involves adding a chemical, such as alum or ferric chloride, to the wastewater to destabilize suspended particles and form larger particles, called flocs. Flocculation involves gentle stirring of the water to encourage the formation of larger flocs. Sedimentation is the process by which the flocs settle to the bottom of a tank, leaving clear water at the top. Disinfection involves the use of chemicals, such as chlorine or ozone, to kill or inactivate microorganisms in the water. This can be an important step in wastewater treatment to ensure that the water is safe to discharge into the environment. pH adjustment involves adding chemicals, such as lime or sulfuric acid, to adjust the pH of the water to a level that is suitable for treatment or discharge (Qasem e*t al*., 2021; Nimesha *et al*., 2022). Chemical treatment can be used in combination with other treatment methods, such as biological treatment or filtration, to achieve the desired level of treatment. However, chemical treatment can also have some drawbacks, such as the generation of chemical sludge, which requires proper handling and disposal. Overall, chemical treatment is an important component of wastewater treatment and can be an effective method for removing contaminants and pollutants from the water. However, it requires careful consideration of factors such as the type of contaminants present, the effectiveness of the chemicals used, and the environmental impact of the treatment process (Grégorio and Eric, 2018; Abuhasel e*t al*., 2021).

Physical Treatment: Physical treatment is the first stage in the treatment of wastewater. It involves the removal of large solids, organic matter, and debris from the wastewater. The main physical treatment processes used in wastewater treatment include (Figure 3):

Screening: This process involves the removal of large solids such as sticks, rags, plastics, and other debris. The wastewater is passed through a series of screens with different sized openings to capture the larger materials (Jain e*t al*., 2021).

Grit Removal: Grit is the term given to heavy, inorganic materials such as sand and gravel that are present in the wastewater. Grit removal involves the use of sedimentation tanks or cyclones to separate the grit from the wastewater (Reddy, and Abhilash, 2022).

Sedimentation: This process involves the settling of suspended solids in the wastewater to the bottom of a tank. The settled solids are called sludge, and the clarified water is removed from the top of the tank (Prasad, 2019).

Flotation: Flotation is a process used to remove fats, oils, and greases from the wastewater. Air is introduced into the wastewater, and the bubbles attach to the fats, oils, and greases, causing them to float to the surface where they can be skimmed off (Zulkefli e*t al*., 2022).

Equalization: Equalization tanks are used to balance the flow and quality of wastewater. They are used to store wastewater during periods of high flow or high pollutant loadings and release it over a longer period of time to the treatment plant (Nyamjav e*t al*., 2023).

Aeration: Aeration is a process that adds air to the wastewater to promote the growth of aerobic bacteria. The bacteria use the organic matter in the wastewater as food, and as they grow, they break down the organic matter (Mathew *et al*., 2022).

Filtration: Filtration is the final stage of physical treatment. It involves the removal of fine solids and suspended particles from the wastewater. The wastewater is passed through sand filters or other media to remove the remaining solids (Koul e*t al*., 2022).

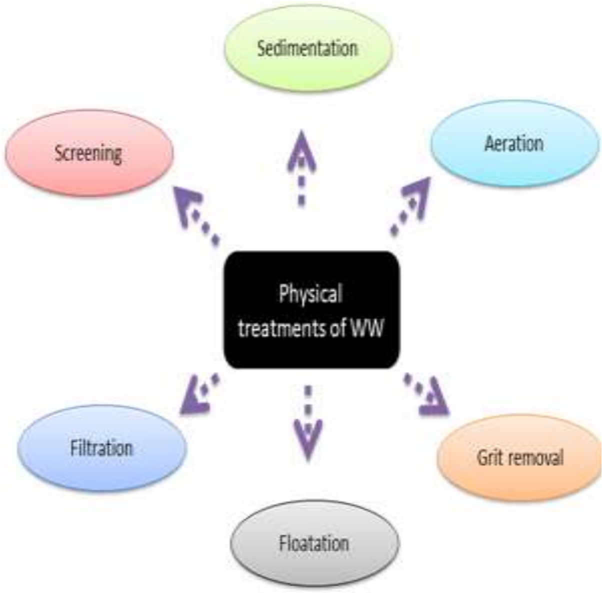

Fig 3: Physical treatment of wastewater

Advanced Oxidation Processes: Advanced Oxidation Processes (AOPs) are a group of techniques that are used to treat wastewater containing highly toxic, recalcitrant or non-biodegradable pollutants. These techniques are effective in destroying or converting complex organic pollutants into simpler, more biodegradable compounds. AOPs involve the generation of highly reactive oxidizing species that are capable of destroying organic compounds by chemical reactions. Some of the commonly used AOPs in wastewater treatment include:

Ozone Treatment: Ozone is a highly reactive oxidizing agent that can be used to treat wastewater. It is generated by passing oxygen through an electrical discharge. Ozone reacts with organic compounds in the wastewater, breaking them down into simpler compounds that are more biodegradable (Zahmatkesh e*t al*., 2022).

Hydrogen Peroxide Treatment: Hydrogen peroxide is another oxidizing agent that can be used to treat wastewater. It is often used in combination with UV light or ozone to produce hydroxyl radicals, which are highly reactive and capable of breaking down organic compounds (Garrido-Cardenas e*t al*., 2019; Kokkinos e*t al*., 2021).

UV Treatment: Ultraviolet (UV) radiation is used to treat wastewater by generating highly reactive hydroxyl radicals that can oxidize organic compounds. UV treatment is often used in combination with hydrogen peroxide to enhance the production of hydroxyl radicals (Andrades e*t al*., 2022).

Fenton's Reagent: Fenton's reagent is a mixture of hydrogen peroxide and iron salts that can be used to treat wastewater. The iron ions catalyze the decomposition of hydrogen peroxide, producing highly reactive hydroxyl radicals that can break down organic compounds (Xu e*t al*., 2020).

Photo-Fenton Treatment: Photo-Fenton treatment is a combination of UV radiation and Fenton's reagent. The UV radiation produces hydroxyl radicals from the hydrogen peroxide, while the iron ions from the Fenton's reagent act as a catalyst. This process is highly effective in treating wastewater containing recalcitrant pollutants. Overall, AOPs are effective in treating wastewater containing highly toxic, recalcitrant or non-biodegradable pollutants. However, these techniques can be expensive and require specialized equipment and expertise. Therefore, their use is often limited to industrial applications or treatment of highly contaminated wastewater (Ghime, and Ghosh, 2020; Kastanek e*t al*., 2023).

Electrochemical Treatment: Electrochemical treatment is a promising technology for wastewater treatment that involves the use of electricity to remove contaminants from wastewater. This technology utilizes electrodes to facilitate chemical reactions that break down or convert pollutants in the wastewater into less harmful substances. Electrochemical treatment can be used to treat various types of wastewater, including industrial wastewater, municipal wastewater, and agricultural wastewater. The treatment process can be used to remove a wide range of pollutants, including organic compounds, heavy metals, and nutrients such as nitrogen and phosphorus (Priyadarshini e*t al*., 2022). There are different types of electrochemical treatment technologies, including electrocoagulation electrooxidation electroflotation, and electrodialysis. Electrocoagulation involves the use of electrodes to generate coagulants that react with pollutants in the wastewater, forming flocs that can be easily separated. Electrooxidation involves the use of anodes and cathodes to generate oxidants that react with the pollutants, converting them into less harmful substances. Electroflotation involves the use of electrodes to generate gas bubbles that float the pollutants to the surface, where they can be skimmed off. Electrodialysis involves the use of an electrical current to drive ions through a membrane, separating the pollutants from the wastewater. Overall electrochemical treatment offers a promising approach for wastewater treatment, as it is a relatively low-cost and energy-efficient technology that can effectively remove a wide range of pollutants. The selection of a specific technology for water reuse treatment depends on factors such as the quality of the wastewater, the required level of treatment, the available resources, and the intended use of the treated water (Hand, and Cusick, 2021; Mao e*t al*., 2023).

Conclusion: The green approach to wastewater treatment strategies involves utilizing sustainable and eco-friendly methods to treat and manage wastewater. This approach emphasizes the use of renewable energy sources, the reduction of energy consumption and greenhouse gas emissions, and the protection and restoration of natural ecosystems. Overall, the green approach to wastewater treatment strategies has several advantages over traditional approaches. It is more cost-effective, sustainable, and has a lower environmental impact. Green technologies such as constructed wetlands, phytoremediation, and anaerobic digestion have proven to be effective in treating wastewater while minimizing negative environmental impacts. However, implementing a green approach to wastewater treatment strategies may require significant investment in research and development, as well as changes in existing policies and regulations. It may also require a shift in societal attitudes towards wastewater treatment and the environment. The green approach to wastewater treatment strategies is a promising way to address the increasing challenges of wastewater management while promoting sustainability and environmental protection.

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