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Review Article

Phycoremediation in wastewater treatment: A thorough analysis of sustainability's advantages and difficulties

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ABSTRACT
The growing volume of wastewater, driven by population growth, bettered living norms, and profitable development, demands effective treatment. Conventional styles, like centralized aerobic shops and lagoons, handle domestic and artificial wastewater in advanced nations. As water costs rise, treated wastewater is decreasingly viewed as a recyclable resource, reducing reliance on gutters, lakes, and groundwater while mollifying water failure. A methodical review of 106 studies (2005 – 2024) anatomized the profitable and environmental sustainability of innovative treatment technologies. These include bioreactors, anaerobic ammonium oxidation, membrane bioreactors, advanced oxidation, nanotechnology, sludge operation, sequencing batch reactors, and IoT- and AI- enabled systems. Sanatorium wastewater and resource recovery, similar as energy and agrarian exercise, were also addressed. These technologies prioritize contaminant junking, public health, and resource conservation while reducing environmental vestiges. This review evaluates their performance, cost- effectiveness, and implicit for advancing sustainable wastewater treatment, fostering a indirect frugality and environmental protection.

1. Introduction

Wastewater treatment is at the cross road of environmental sustainability and public health, and it's critical in icing the responsible operation of water systems. As the world population continues to grow and urbanization accelerates, the necessity for adequate wastewater treatment solutions becomes less important [1]. Monitoring, analyzing, and controlling water resources can be completely transformed by smart water management, which is made possible by the smooth communication between IoT devices and AI algorithms. With an emphasis on incorporating IoT and AI into water and wastewater treatment, this analysis investigates and assesses the level of smart water management today [2]. Wastewater operation remains the most significant threat to environmental sustainability and public health. Adsorption has been established as one of the most effective and protean styles for wastewater treatment due to its simplicity, efficacy, and ability to remove a wide spectrum of contaminants. Actuated carbon, derived from natural materials, has been critical for drawing water since the early twentieth century because it can remove a wide range of adulterants. Still, the search for better, cheaper, and more environmentally friendly cleaning supplies continues. This is because wastewater is becoming more intricate and environmental laws are becoming harsher, pushing for new and advanced styles beyond the traditional bones [3].

IoT technology in wastewater management can offer real-time effluent quality and treatment efficiency monitoring in wastewater treatment plants, enabling early detection of inefficiencies or malfunctions and assisting in the prevention of possible environmental and health hazards. Additionally, IoT technologies allow for remote and autonomous operations, which improve system efficiency and decrease the need for human intervention by enabling remote monitoring and control of water and wastewater infrastructure components like pipelines, pumps, manholes, and valves. The gathering and analysis of data from infrastructure systems has been further improved by developments in IoT technologies, similar as edge computing, machine literacy (ML), and artificial intelligence (AI). This has bettered operation and decision-making in the field of water and wastewater operations. These difficulties make it abundantly apparent that wastewater must be treated before being discharged into undersea terrain. In order to maintain biodiversity and force safe drinking water, wastewater treatment is a critical issue. By tackling poverty and disease, wastewater treatment supports sustainable development and aligns with the key elements of the 2030 Sustainable Development Goals (SDGs). Conventional wastewater treatment techniques have been used, including distillation systems and physicochemical procedures including ion exchange, adsorption, reverse osmosis, and UV treatment. But these methods are time-consuming, costly, and ineffective, and they frequently produce sludge [4].

For the purpose of creating efficient waste management plans and encouraging sustainable behaviors, it is essential to comprehend the trends in global garbage generation. There are strategies for hazardous waste management that lower risks and promote environmentally conscious behavior. These include stringent rules, resource recovery and recycling innovations, and stakeholder participation. Ensuring that all regulations are followed and that various industrial sectors are successfully enforced is the biggest problem in handling hazardous waste. To guarantee that stringent waste management regulations are continuously adhered to, cooperation between governmental entities, corporations, and communities is required [4]. Wastewater treatment leads to sustainable water resource management" is the qualitative thesis for this study. This suggests that wastewater treatment prevents the possible reduction of natural coffers while guaranteeing there's enough water to meet people's demands. The degree to which this study delves into the relationship between wastewater treatment and sustainable water resource operation and operation. Using data from other studies, the exploration aims to examine this idea. The test will also look at how important sustainability is bettered by wastewater treatment styles [5].

Heavy Essence, antibiotics, fungicides, endocrine disruptors, colourings, and polycyclic sweet hydrocarbons are among the several pollutants set up in wastewater. Pollutants have a harmful influence on both the environment and human health. To address this issue, multitudinous technologies have been developed, including rear osmosis, chemical rush, adsorption, and photodegradation, nonetheless, there are disadvantages to these treatments, such as high implementation and operation costs, poor removal effectiveness, and hazardous residues. One of the new and most sought-after methods for treating wastewater is nanotechnology. Because of their better qualities arising from the nanoscale effect, many nanomaterials have been targeted to reduce attention of dangerous adulterants in wastewater. Nanomaterials have a high face-to-volume ratio, excellent adsorption properties, and enhanced reactivity. Unmatched eventuality for creating further effective catalysts and redox systems is handed by nanomaterials [6]. Resolved Better methods for creating antiviral, antibacterial, or antimicrobial compounds for water treatment using green nanotechnology are desperately needed. According to recent research, nanoparticles have very promising antiviral and antibacterial qualities. The antibacterial and antimicrobial properties of these nanoparticles, as well as the application of these antibacterial materials in water treatment, were thoroughly explained [7].

In the fields of environmental sustainability and health science, nanotechnology has proven to be a blessing in overcoming a number of problems. Our planet's supply of clean water is running low, thus wastewater must be cleaned up to meet our needs. Various kinds Nanoparticles (NPs), nanocomposites, and functionalized nanostructures can be employed to clean wastewater. These can be used to produce effective membranes for desalination and sanctification, antimicrobial agents to decontaminate water, photocatalysts to remove dangerous colourings and colours from wastewater, nano- absorbents to remove heavy substance from weakened water, largely active NPs to chelate heavy substance, etc [8]. The wastewater treatment process's operating and running costs are greatly decreased when biochar is reactivated (regenerated) after the adsorption process and used for multiple cycles. Put another way, the high recycling and reuse rates of adsorbents are essential to the financial viability of wastewater treatment. In order to reuse adsorbents, a number of regeneration approaches have been developed, proposed, and assessed. The type of adsorbent (either pristine or composite), its characteristics, and the kind of adsorbate all affect the methods [9].

The wastewater produced by domestic homes is frequently collected by a reticulated sewerage system and either reused at a wastewater treatment factory or treated and disposed of on-point. Given that India is among the world's citified nations, utmost homes have a reticulated water force and a seamster system that's overseen by a external or statutory authority [10]. Additionally, HWW has a lower biodegradability indicator than external wastewater, which makes it gruelling to treat using traditional natural systems. The ecosystem is seriously hovered by several of the refractory organic composites set up in HWW, similar as PhACs, which are extremely dangerous and have veritably low drinking water original limit (DWEL) values[11]. Indeed after HWW is treated, contagions, ARB, and ARG persist, and their discharge into the submarine ecosystem constitutes a serious environmental threat. The most common heavy metals include lead (Pb), zinc (Zn), mercury (Hg), nickel (Ni), cadmium (Cd), copper (Cu), chromium (Cr), arsenic (As), and zinc (Zn) essence. Indeed though traces of these heavy essences can be set up, they're still dangerous. Generally set up in wastewater, the forenamed essence as well as others like tableware (Ag), iron (Fe), manganese (Mn), molybdenum (Mo), boron (B), calcium (Ca), antimony (Sb), cobalt (Co), and other rudiments must be barred [12].

Recent studies have focused on certain methods of eliminating heavy metal ions, such as increased oxidation processes, membranes, Electrocoagulation (EC), adsorption with natural and synthetic adsorbents, magnetic field application, etc. These research focused on the advantages and downsides of a particular wastewater treatment method, particularly the elimination of heavy metals [13]. The amount of treated wastewater reuse has increased rapidly; in China, the USA, Europe, and even Australia, volumes have increased by 10 to 29% every year, and in Australia, by as much as 41%. China has more wastewater reuse than any other country in Asia, including Vietnam, India, and Pakistan, with an estimated 1.3 million hectares. Only about 37.6% of India's urban wastewater is currently treated, according to estimates. With 90 of the recovered water being used for agrarian land irrigation, Israel is the biggest stoner of treated wastewater, numerous low- income countries in Asia, Latin America, and Africa use undressed wastewater to irrigate. still, treated wastewater is used in middle- income countries like Saudi Arabia, Jordan, and Tunisia for [14]. Numerous elements from diverse sources, such as garbage [3]. Both manmade and natural materials have been Delved as adsorbents for the junking of certain heavy essence from wastewater or water sources. Both treated and untreated versions of these materials can be used. The main justification for using adsorption in cleanup processes is its advantages, which include its simplicity of use and operation, cheap production costs, low production of waste and sludge, and most importantly, its capacity for regeneration or reuse for multiple cycles [15].

1.1 Background, status and need of WWT

Sustainability and Wastewater Treatment: The phrase "wastewater as a resource" signifies a change of perspective from something that was before viewed as a liability to something that is necessary to solve the problems with sanitation and water supply. But until technology is introduced to make the change a reality, calling wastewater a resource is just a meaningless statement. Wastewater has long been viewed as a liability and a possible cause of illness. In order to reduce harm to the human population, people prefer to avoid wastewater by establishing pathways for the safe disposal of the chemicals, sludge, and other sold stuff found in wastewater. People, those who live in dry and semi-arid regions, on the other hand, must constantly figure out how to convert wastewater into valuable resources for their houses and companies. Additionally, wastewater treatment plays an important role in the circular economy, which considers wastewater a resource rather than a burden. To lessen the demand on natural resources and improve environmental sustainability, the circular economy prioritizes material and product reuse and regeneration. Treatment of wastewater has grown in importance as a source of clean water, fertilizer, nutrients, and energy. For example, it is an important source of biogas that may be used in homes and businesses. By using it to generate electricity, we can lessen our need on fossil fuels and the strain on natural resources.

The majority of governments worldwide have recognized that it can be put to better use instead of being dumped into neighboring lakes, rivers, or seas. Additionally, policymakers looking for alternate sources of economic growth have shown a great deal of interest in it due to its many advantages. The ability of wastewater to be treated to meet a variety of needs, including those of industry and agriculture, is one of its greatest benefits. Additionally, wastewater byproducts like cleaned sludge can be turned into fertilizer. Without using potentially hazardous pesticides, some of the by-products provide nutrients to enhance plant development and output. Wastewater, for example, can be treated to a certain quality required for irrigation and other farming uses. The amount of clean drinking water available can also be increased by further treating wastewater. When a product would otherwise be completely wasted, wastewater treatment makes sure that nothing is wasted. A total of 16,652.5 MLD of wastewater is produced by 299 class-1 cities. Twenty-three metro areas generate roughly 59% of this. About 23%, the majority of wastewater produced in class-1 cities originates from the state of Maharashtra, with 31% coming from the Ganga river basin. Only 72 percent of processed wastewater is collected. 92 of the 299 class-1 cities have more than 50% population coverage, and 160 have sewerage systems serving more than 75% of the population. Sewerage facilities are now provided to 70% of the population in class-1 cities, up from 48% in 1988. There are three types of sewerage systems: piped, closed, and open. This study's primary goal was to review the aerobic sludge treatment of residential sewage in order to guarantee efficient discharge and/or reuse/recycling [16]. Out of 16,662.5 Only 4037.2 MLD (24%) of the MLD of wastewater produced is treated before release, whereas the remaining 12,626.30 MLD is disposed of untreated. Only 49 cities have primary and secondary treatment facilities, and 27 cities have only primary treatment facilities [17].

1.1.1 Need of sewage treatment

The complex organic molecules found in wastewater are broken down into simpler, stable and doorless components via physico-chemical processes or the employment of microbes (biological treatment). The following negative environmental effects result from releasing untreated wastewater into surface or groundwater bodies and/or lands: A significant amount of foul-smelling gases may be produced as a result of the organic compounds in wastewater breaking down.

1. Among other undesirable effects, dumping untreated wastewater (sewage) with a high organic matter content into a The river or stream will deplete dissolved oxygen to meet the wastewater's Biochemical Oxygen Demand (BOD), lowering the stream's dissolved oxygen and killing fish.
2. Lakes and streams may become eutrophic due to nutrients in wastewater that may also encourage. The proliferation of aquatic vegetation and algal blooms. Nutrients in wastewater can cause eutrophication in lakes and streams, supporting the growth of aquatic plants and algae blooms.
3. Untreated wastewater typically has a high concentration of pathogenic, or disease-causing, microorganisms and hazardous substances found in the human digestive tract or in some industrial waste. These might contaminate the ground where the sewage is disposed of or the body of water. For the reasons mentioned above, wastewater treatment and disposal are not only desirable but also necessary [17].

1.1.2 Wastewater reuse in the industrial, municipal, and domestic sectors

Municipalities use Treated wastewater is used for a variety of purposes, including road landscaping, parks, playgrounds, golf courses, and toilet flushing. Cooling systems, aquaculture, agricultural irrigation, food processing, and other high-rate water applications are some examples of industrial wastewater reuse. In Middle Eastern countries with limited water supplies, dual distribution systems will soon deliver high-quality, treated wastewater for toilet flushing in hotels, office buildings, and other facilities. In India, wastewater is utilized for a variety of purposes, including boiler feed, irrigation, gardening, flushing, air conditioning system cooling, and process water for businesses. China has a national strategy that promotes the development of water-efficient technology as well as the repurposing of recovered urban wastewater, first for agricultural purposes, then for industrial and municipal uses. In Japan, reclaimed wastewater is used for flow augmentation to generate "urban amenities" such as green spaces, industry, stream restoration, and toilet flushing [16].

1.1.3 Importance of wastewater reuse

Despite having 6% of the world's population, the MENA area only has 1% of Freshwater resources. The countries in the region rely on seasonal rainfall and a few rivers, some of which convey runoff from neighboring countries. Additionally, they usually depend on aquifers that are fragile and often non-renewable. However, new and innovative water technologies are required to handle the major problems with the world's water situation, which are mostly brought on by population growth and climate change, in order to maintain a steady supply of water and decrease wastewater contamination. Reusing wastewater appears to be the most effective technique for tackling scarcity in the Mediterranean. This scarcity is caused by water stress, population increase, and climate change. The option for Mediterranean countries is to use non-traditional water sources, such as treated wastewater, rather than raw water from rivers or aquifers. Recycled wastewater is the only resource that grows at the same rate as the economy. In any event, the goal of water reuse is to help end the anthropogenic water cycle and allow for the sustainable reuse of existing water supplies. This circular economy strategy improves countries' water sovereignty by providing them with a consistent resource on their land for agricultural irrigation. When combined with water resource management, it can be considered an important aspect of pollution prevention and water management techniques [18].

1.1.4 Wastewater treatment and sustainability

Wastewater treatment rates are still low in a number of MENA countries. Many wastewater treatment plants are not well-maintained and run over their design capacities. It's also worth noting that agriculture consumes the majority of water in most MENA countries. Crop agriculture uses an average of 86% of the water recovered for various water consumer industries. Water usage is 8% for families and 6% for companies. It clearly shows the volume of wastewater produced versus the volume of untreated wastewater in the MENA region.

For example, all wastewater collected in Bahrain is treated with activated sludge and tertiary treatment methods, whereas less than 10% of wastewater collected in Iran, Lebanon, Morocco, and Libya is treated [19]. Even though there are other sources of water contamination, such as residences, workplaces, mines, and infiltration, industrial water use remains one of the most significant. The four main types of water are industrial wastewater, residential wastewater, agricultural water, and rain water (runoff from impermeable surfaces). The final category includes cooling water, washing effluent (with varying compositions), and manufacturing or process water (biodegradable and/or potentially hazardous). Process waters, often known as wastewaters or effluents, are responsible for the majority of problems. A crucial difference exists between drinking water sources, which are usually lakes, reservoirs, or rivers, and wastewater: Most sources of drinking water have very modest levels of pollutants when compared to wastewaters from industrial processes. Of course, the amount of hazard depends on its composition, which is influenced by its industrial origin. The challenges that arise during wastewater treatment are usually somewhat complex because the effluent comprises a variety of pollutants depending on its source. As a result, there are numerous varieties of effluent to manage, each with unique properties that require distinct treatment procedures. When decontamination is required due to water pollution, the most effective purification procedure should be used to meet the decontamination goals.

1.1.5 Technologies available for contaminant removal

Physical, chemical, and/or biological techniques and operations are frequently used in conventional wastewater treatment to remove solids from effluents, including colloids, organic matter, nutrients, and soluble pollutants (metals, organics, and so on). Many approaches that can be divided into three categories—new removal techniques, traditional methods, and established recovery procedures—have been used. The advantages and disadvantages of a number of distinct approaches were investigated. As a result, the method selected will depend on the effluent's characteristics. In addition to cost, each treatment has limits related to feasibility, efficiency, practicability, dependability, environmental impact, sludge creation, operating difficulty, pre-treatment requirements, and the development of potentially hazardous by-products. However, for economical and scientific reasons, the industrial sector only employs a small portion of the numerous wastewater treatment processes already outlined. Most typically, physicochemical and/or biological approaches are used to remove contaminants from effluents, with research focusing on novel or less expensive combinations of efficient systems [19]. Applications of anammox bacteria are the basis of new nitrogen removal technologies that are presently being evaluated in Sweden on a full technical scale as well as at the pilot size. These methods are employed for mainstream treatment as well as for treating reject water following the dewatering of digested sludge. The Membrane Aerated Biofilm Reactor (MABR), an aerated membrane bioreactor containing a layer of biofilm, provides the basis for another tried-and-true method of nitrogen removal. It is difficult for many European nations, including Sweden, to remove pharmaceutical residues from wastewater using ozone and activated carbon. The development of membrane treatment methods for wastewater is another technological advancement.

The application of Membrane Biological Reactor MBR is presently undergoing pilot investigations. Technically speaking, it will be the biggest membrane installation in the world. Many wastewater treatment plants are also conducting substantial research on enhanced biogas production and nutrient recovery [20].

This review work primary subjects are the need for wastewater treatment and its function in sustainable water resource management. This review work will also examine the various wastewater treatment systems and how sustainable they are. The purpose is to identify and recommend a suitable wastewater treatment procedure for use in both commercial and residential settings to ensure that no water is wasted, contaminated, or inappropriately managed. The goal of this study is to gain a thorough understanding of the opportunities and difficulties that various locations encounter while trying to improve their wastewater treatment capacities. By combining the body of available knowledge, this review seeks to identify important trends, obstacles, and possibilities in the field. Additionally, it aims to clarify the possible advantages of intelligent water management in terms of resource efficiency, environmental sustainability, and resilience to. In order to create sustainable and successful water management plans, wastewater treatment is essential. The purpose of this review is to add to the larger discussion about smart water. This assessment also looks at future trends in wastewater cleaning and how these advances can affect costs and the environment. Analyzing these technologies' suitability for various waste streams, sectors, and geographical areas is the goal of the study.

This study's main goal is to analyze and appraise cutting-edge wastewater treatment technologies, with an emphasis on their scalability, affordability, and environmental performance. We attempted to clarify how these developments can result in more effective and sustainable methods of ensuring clean water by demythologizing complicated technology and its ramifications, considering the larger significance of environment.

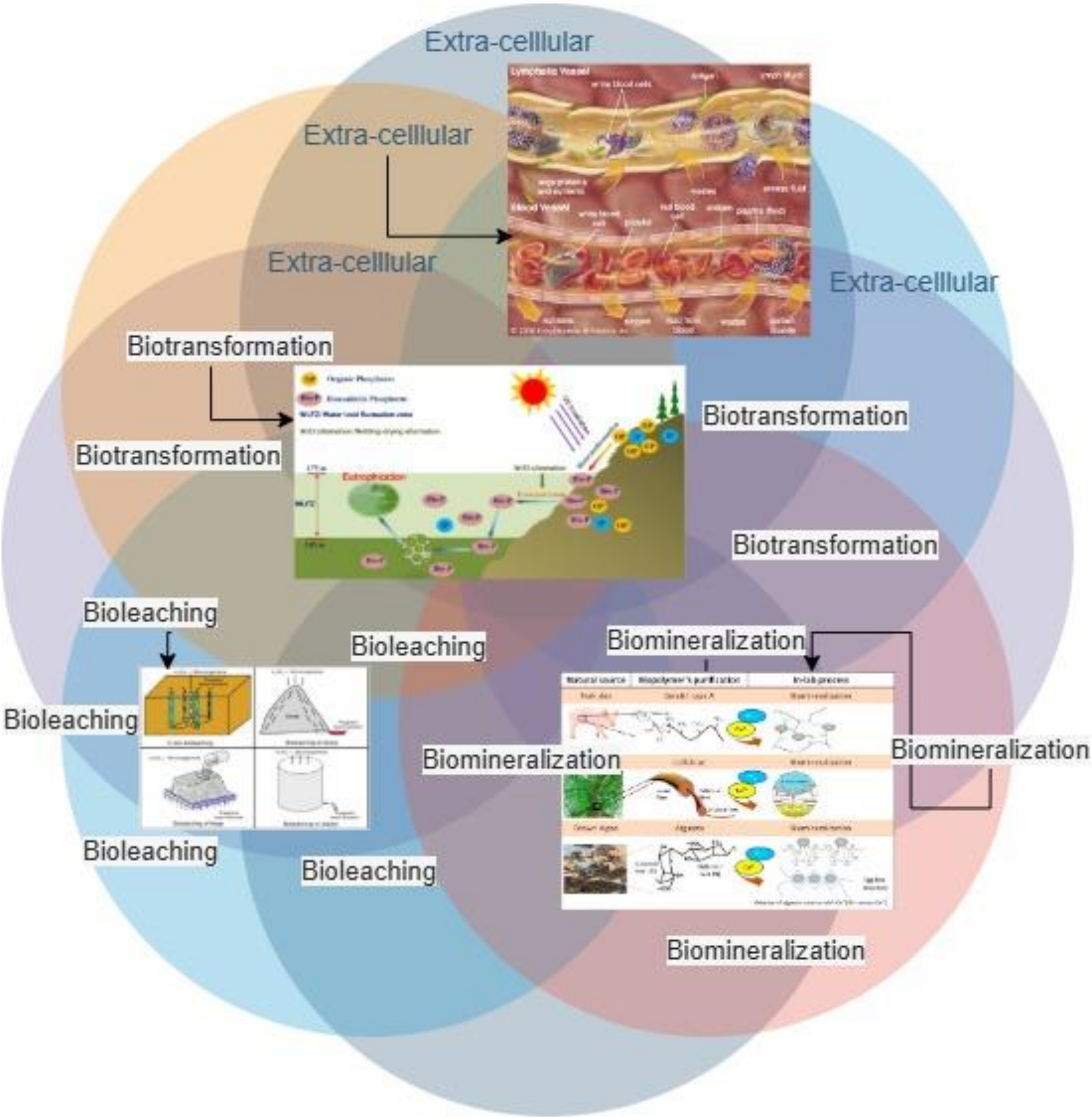

Figure 1: Heavy metal and metalloid bioremediation in microalgae via accumulation and extracellular and intracellular biotransformation. Additionally demonstrated are biotransformation, bioleaching, and biomineralization.

2. Methodology

2.1 Conventional WWT techniques

Conventional wastewater treatment methods are widely used to treat municipal and industrial wastewater before discharging it into the environment or reusing it. These methods are generally categorized into primary, secondary, and tertiary treatments.

2.1.1 Conventional methods

Conventional water purification methods, such as coagulation, sedimentation, filtration, and chlorination, have been widely used for decades. These processes are typically sequential and aim to remove suspended particles, pathogens, and dissolved substances.

- **Coagulation and flocculation**: These procedures entail the addition of chemicals called coagulants, which force tiny particles to group together into bigger aggregates called flocs. Sedimentation and filtration can then be used to remove these flocs.
- **Sedimentation**: This is a gravity-based process where the heavier flocs settle at the bottom of a sedimentation tank, allowing clearer water to be drawn off the top.
- **Filtration**: Water travels through filters of different compositions (sand, gravel, and charcoal). to eliminate some of the dissolved and residual suspended particles. organic and inorganic compounds.
- **Chlorination**: Chlorine or chlorine compounds are added to disinfect the water by killing bacteria, viruses, and other pathogens. These methods have been effective in reducing waterborne diseases and providing safe drinking water on a large scale [21].

2.1.1.1 Primary treatment

The purpose of this first stage is to rid raw wastewater of floating, suspended, and bulk solids. It involves sedimentation by gravity to eliminate suspended solids and screening to capture solid objects. Although chemicals can be used to speed up the sedimentation process, this physical solid/liquid separation is mechanical in nature. During this stage of treatment, the BOD in the entering wastewater is decreased by 20-30%, as are the total suspended particles by nearly 50-60%.

2.1.1.2 Secondary (biological) treatment

The dissolved organic debris that eludes first treatment is removed in this step. The organic matter is eaten by microbes, who then transform it into energy, water, and carbon dioxide for their own development. In order to eliminate more suspended particles, the biological process is followed by further settling. Over 85% of the suspended solids and biological oxygen demand (BOD) can be eliminated by secondary treatment. This procedure eliminates the biological sludge is separated from the clean water by carbonaceous contaminants that accumulate in the secondary settling tanks. In a biogas plant, this sludge can be used as a co-substrate with other waste materials to produce biogas, which is a mixture of CH_4 and CO_2. It produces heat and power to distribute additional energy. The clear water that remains is subsequently either nitrified or denitrified to remove carbon and nitrogen. In addition, a sedimentation basin disinfects the water with chlorine. At this point, the water may still include various metal, chemical, and microbiological contaminants. As a result, before entering a disinfection tank, the water must first pass through filtration before being reused, such as for irrigation. Here, wastewater is disinfected using sodium hypochlorite. The treated water is deemed fit for irrigation after this process. In the gravity thickening tank, solid waste produced during the primary and secondary treatment phases is further treated while receiving a constant air flow. The solid waste is then moved to a tank for stabilizing lime and another for dewatering centrifuges. At this stage, treated solid waste is produced, which can then be processed for a number of uses, such as land-filling, fertilizer, and construction. Other methods, such as methanogenic reactors, artificial wetlands, microbial fuel cells, trickling filters, anaerobic treatments like up-flow anaerobic sludge blanket (UASB) reactors, and ponds (aerobic, anaerobic, facultative, and maturation), have been developed and are currently being used in full-scale reactors in addition to activated sludge. Wastewater has been treated in UASB reactors for many years. The COD loading rate in their study stayed at 1.21 kg COD/m^3/day after 200 days of testing. They removed 85% of the COD on average.

2.1.1.3 Tertiary or advanced treatment processes

When specific components, contaminants, or pollutants are not completely eradicated after secondary treatment, the tertiary treatment procedure is utilized. Thus, tertiary treatment techniques ensure that wastewater is free of more than 99 percent of all pollutants. Water is treated alone or in combination with cutting-edge procedures such as O3 (ozone exposure), UV (ultraviolet light treatment), and US (ultra sonication) to make it safe for human consumption. This method reduces the remaining bacteria and heavy metal pollutants in treated water. To get rid of any contaminants, the secondary treated water is first ultrasonically cleaned, then subjected to UV light and finally run through an ozone chamber. Physical membrane disintegration and free radical assault are two proposed processes that render cells inviable during the US [37, 38]. The combination of O3, UV, and US produces free radicals, which attach to biological pollutants' cell membranes. Chemical oxidants can infiltrate the cell and target internal components once the cell membrane has been broken components. As a result, the United States, either alone or in combination, promotes germ deagglomeration and enhances the effectiveness of additional chemical disinfectants [31-37] also investigated a combined treatment technique and discovered that it was a highly effective method for treating textile effluent. The effectiveness of using ultrasound and UV light together as a pre-treatment step [29, 30]. To optimize the wastewater disinfection process, it was also compared to various combinations of UV and ultrasonic radiation with TiO_2 photocatalysis [31] and ozone. We recommend testing an essential component of our wastewater treatment strategy is the quality of treated water at every stage of the treatment process. Following the meeting with the necessary purification standards, the treated water can be used for drinking, irrigation, and other home applications [28].

2.1.2 Limitations of conventional methods

Despite their widespread use and effectiveness, conventional water purification methods have several limitations.

- **Inadequate for Emerging Contaminants**: Conventional methods are often ineffective against Emerging pollutants include medications, personal care goods, and endocrine disrupting substances. These pollutants can pass through typical treatment techniques, posing serious health hazards.
- **Chemical Residuals**: Processes like chlorination can produce hazardous byproducts, such as haloacetic acids (HAAs) and trihalomethanes (THMs), which are linked to a variety of health issues, including cancer.
- **Energy and Resource Intensive**: Many conventional methods demand considerable energy inputs and chemical additions, which can be expensive and environmentally harmful in the long run.
- **Limited Pathogen Removal**: While effective against many pathogens, some resistant strains of bacteria and viruses can survive conventional treatment processes, necessitating additional treatment steps [22].

2.2 Advanced WWT technologies

In order to overcome the shortcomings of traditional techniques, a number of sophisticated waste water treatment technologies have been developed. These technologies leverage recent scientific and engineering advancements to provide more effective and sustainable water treatment solutions.

2.2.1 Membrane Bioreactors (MBRs)

MBRs improve solids removal and generate high-quality effluents by combining membrane filtration with biological treatment. Because of its small size, low environmental impact, and excellent treatment effectiveness, the technology has become well-known throughout the world. But problems like membrane fouling and high operating costs still exist, requiring constant research and improvement.

2.2.2 Advanced oxidation processes (AOP)

In order to degrade persistent pollutants, AOPs produce extremely reactive hydroxyl radicals. Recalcitrant chemicals that are ineffectively handled by traditional techniques are addressed by this technology. Although AOPs show potential, energy-intensive procedures and the requirement for meticulous optimization to avoid the production of hazardous byproducts restrict their broad implementation.

2.2.3 Constructed wetlands

In order to treat wastewater, artificial wetlands mimic natural ecosystems. They improve the elimination of pollutants by fostering chemical, biological, and physical processes. Constructed wetlands are attractive due to their affordability and versatility, especially in decentralized environments. However, vegetation, climate, and hydraulic conditions can all affect how well they work.

Smart water management technologies

The Internet of Things and artificial intelligence have transformed the objective of effective and sustainable water management. These state-of-the-art technologies serve as the foundation for intelligent water management systems when they are seamlessly integrated. Water infrastructure monitoring and control are improved by the combination of IoT and AI. It gives decision-makers access to sophisticated analytics and forecasting tools. In order to demonstrate how smart water management technologies transform water governance, this research examines their complex inner workings. IoT technologies are essential for improving water infrastructure monitoring and control. In water treatment plants, smart sensors continuously monitor crucial characteristics including turbidity, pH levels, and chemical concentrations by [43]. Throughout the distribution network, IoT-enabled devices deliver real-time information about water flow, pressure, and leak detection. At the consumer end, smart meters equipped with IoT capabilities enable precise monitoring of water consumption, facilitating efficient billing and encouraging water conservation. The seamless integration of IoT in water infrastructure improves the accuracy and timeliness of data collection and enables remote monitoring and control. This capability is particularly valuable for early detection of anomalies, preventive maintenance, and rapid response to emergencies, contributing to the overall resilience of the water management system [39-41].

AI technologies bring intelligence to smart water management systems, particularly in optimizing water treatment processes. AI systems that use machine learning algorithms may examine past data to spot patterns, identify trends, and forecast future changes in water quality. AI helps optimize energy use, chemical doses, and operational efficiency in water treatment. When IoT and AI technologies are seamlessly combined to create a comprehensive and adaptable system, smart water management's full potential becomes apparent. The continuous data streams from IoT devices serve as inputs for AI algorithms, generating insights and actionable recommendations. This closed-loop integration enables real-time decision-making, allowing water management systems to respond to changing conditions dynamically. In conclusion, integrating IoT and AI technologies heralds a new era in water governance. Smart water management systems, fortified by the seamless collaboration of these transformative technologies, transcend traditional approaches, offering a proactive and adaptive model. By providing real-time insights, optimizing operations, and predicting potential issues, these technologies empower decision-makers to navigate the complexities of water management with unprecedented efficiency. As we embrace the digital age, the convergence of IoT and AI is a beacon, paving the way for a future with more resilient and sustainable water resources [20].

Carbon-based nanomaterials

One of the non-metallic elements is carbon. Coal reserves are the main source of carbon. It ranks sixth on the list of most abundant elements and is the second most common element in the human body, behind oxygen. Because of their non-toxicity, abundance, ease of preparation, high surface area and porosity, stability structure, and high sorption capacity—particularly in the removal of dyes and heavy metals—a variety of nanomaterials based on this compound have found extensive use in wastewater treatment over the past few decades. Adsorption is one of the most popular methods for treating water since it eliminates both organic and inorganic contaminants. While immersion is the saturation or dissolution of a substance in a liquid or solid, adsorption is the process of drawing and collecting gaseous or liquid solutes on an adsorbent, which is frequently a solid patch. Sorption is the combination of adsorption and immersion, whereas desorption is the opposite of adsorption. There are two types of adsorption processes: chemisorption and physisorption. Van der Waals forces pull the motes, the adsorbent, and the adsorbate together in physisorption, while chemical bonds bind the motes to the adsorbent's surface in chemisorption. The potential to remove impurities from water determines an adsorption process's performance, which is almost directly correlated with the adsorbent's adsorption capacity. The face features (specific face area), active areas on the face, and affinity for pollutants all have a significant impact on an adsorbent's adsorption capacity. Because of their large specific surface area and potent active sites, carbon-based nanoparticles are indispensable adsorbents [23].

Membrane process

Membranes are often used to remove pollutants found in water, such as metals, bacteria, or viruses, are classified as physical processes that function by moving particles based on different concentration levels or differences in particle size. Selectivity and membrane permeability are two important parameters that affect a membrane's overall performance. Because a membrane with a higher permeability requires less membrane area to process water, the membrane's initial cost is brought down. In the same way, a purer product is produced by a membrane with greater selectivity. This pressure-driven process requires less energy, which is achieved by increased permeability and selectivity. Biofouling is one of the primary challenges to membrane stability over the long term. The development of particular anti-biofouling chemicals is therefore essential for membrane technology used in wastewater and water treatment. The development of hydrophilic membranes aims to lessen surface biofouling. nevertheless, because bacteria continue to adsorb, grow, and regenerate on polymeric membranes, additional measures are required to manage long-term biofouling.

By incorporating biocidal nanoparticles by surface mixing and functionalization, current research aims to construct antibacterial membranes. These compounds can impart desirable qualities to membranes, such a smooth and hydrophilic surface, boosting the membrane's ability to withstand fouling. Despite the fact that nanomaterials have demonstrated potential in lowering the microbial load from wastewater, the kind of NPs used greatly affects the amount of microorganisms eliminated. In general, nanoparticles use a variety of methods to eliminate bacteria, including as releasing poisonous metal ions (like Age) or directly disrupting microbial cell membranes (like chitosan NPs) [42] and producing ROS (photocatalytic TiO_2, for example) [43]. Notwithstanding their potent antibacterial properties, problems can occur, including the leaching of nanomaterials from the antibacterial membrane and the release of (heavy) metal ions that membranes cannot block. On December 26, 2024, visitors to Technology & Water Science, Vol. 87, No. 12, 2991, downloaded the article from: http://iwaponline.com/wst/article-pdf/87/12/2971/1245861/wst087122971.pdf.

Some nanomaterials may be hazardous, which could endanger the aquatic ecology. When employing multifunctional nanomaterials for antibacterial changes, these factors should be taken into mind. Future studies should also concentrate on controlling the release rate in a fair manner in order to efficiently inactivate bacterial strains and extend the membranes' shelf life [24, 25].

Nanotechnology in wastewater remediation

The fields of biomedical science, environmental applications, biosensors, nanomedicine, targeted drug delivery, imaging, and agnostics have all made use of nanotechnology. Recently, natural compounds and nanotechnology have been used to clean wastewater. By using less energy overall during the synthesis or production process, nanomaterials have been employed to fight water pollution. Prior research has looked at nanoparticle synthesis and recycling as well as their use in wastewater and water treatment. A n overview of the sorption capacities of numerous sorbents based on nanomaterials for various kinds of water contaminants has been provided, as well as a discussion of several NP synthesis strategies. Water nano filtration, electrochemical accelerated oxidation, nano adsorbents, and nano catalysts have all been extensively studied [40]. The many contaminants found in water bodies, such as heavy metals, phenolic resins, dyes, surfactants, and persistent organic pollutants, were studied in literature. This paper discusses NP-assisted photochemical wastewater remediation, chemical wastewater treatment, bioremediation, as well as sono chemical and electrochemical treatments. Because magnetic nanoparticles are used as nano adsorbents, their significance was underlined [24]. The role of nanobiotechnology in wastewater remittal has been exemplified in a number of articles [43] illustrates the various sources of water impurities and the use of nanotechnology in wastewater treatment.

Moving bed biofilm reactors (MBBR)

It combines activated sludge (suspended growth) with biofilter procedures (growth that is connected). For biomass development, the Moving Bed Biofilm Reactor (MBBR) method makes utilization of the entire tank volume. It uses simple floating medium, which act as carriers for related biofilm development. Disruption of air bubbles is what makes biofilm carriers mobile. BOD, nitrogen, and phosphorus can be expelled using this simple treatment framework, which also promotes effective solids separation [23].

Sequential batch reactor (SBR)

The sequencing batch reactor(SBR) process is a progressive suspended growth(active sludge) process in which each main step takes place in a common tank in successive sequence. The aggregate five ways do in a single reactor, which minimizes the print. SBRs can be constructed and operated to ameliorate nitrogen, phosphorus, and ammonia junking while also clearing TSS and BOD. SBR has five stages, which are:

- **Fill**: Biomass that settles during the previous cycle is mixed with wastewater as it fills the tank.
- **React**: To encourage biological growth and celebrate waste minimization, air is introduced to the tank.
- **Settle**: To allow the solids to settle, mixing and aeration are stopped during this phase.
- **Draw**: Water that has been clarified is released.
- **Idle**: Sludge can be eliminated during this phase [26].

2.2.4 Other advanced technologies

Numerous cutting-edge technologies are being investigated for wastewater treatment, including carbon-based nanomaterials, electrochemical therapy, algae-based systems, and nanotech applications. These developments tackle particular issues and hold promise for improvements in productivity, resource recovery, and environmental sustainability. However, more research is needed to determine their scalability and long-term performance. The usage of cutting-edge wastewater treatment technologies has grown dramatically in the United States.

Innovative nutrient removal systems, membrane technologies, and AOPs are being used more and more by companies and municipalities. A greater focus on sustainability and resilience in the face of shifting environmental dynamics is reflected in the movement towards resource recovery and water reuse. The USA's adoption of modern technologies is influenced by a number of elements, such as financing sources, regulatory frameworks, stakeholder willingness to adopt novel solutions, and technological awareness. In order to create an atmosphere that is favorable for the integration of cutting-edge wastewater treatment technologies, government programs and incentives are essential. From simple systems to more sophisticated facilities in urban areas, Africa's wastewater treatment landscape is remarkably diverse. The widespread adoption of new technology is hampered by issues including weak institutional frameworks, poor funding, and limited infrastructure. The confluence of contemporary and conventional therapeutic approaches [27].

3. Results and discussion

Innovative nutrient removal systems, membrane technologies, and AOPs are being used more and more by companies and municipalities. The trend toward resource recovery and water reuse is indicative of a greater focus on sustainability and adaptability in a changing environment. Additionally, the results were graded according to their strength, content validity, bias, and suitability for sustainable resource management and wastewater treatment. "Does treating wastewater result in the management of water resources in a sustainable way?"?" is the question this study aims to answer. According to the study's thesis, wastewater treatment reduces the harmful environmental effects of wastewater, creates sustainable communities, and transforms waste into clean energy and water, all of which contribute to economic and environmental sustainability. The table's supporting data additionally shows the connection between the qualitative variable "sustainable results of wastewater treatment" and "wastewater [23].

3.1 Role of different technologies in WWT

Technology is essential for wastewater treatment because it provides sustainable and efficient methods for removing pollutants and impurities from water sources. Wastewater is handled utilizing a range of methods, such as biological, physical, and chemical processes. Phytoremediation, which includes cultivating algae in wastewater to eliminate pollutants and produce biomass for the manufacture of biofuel, is one such technique. Moreover, biochar and green nanoparticles made from agricultural waste have the ability to remove remaining contaminants from water and wastewater.

Promising opportunities in wastewater treatment are presented by membrane and nanotechnology, particularly carbon nanostructures and nano fillers. In wastewater treatment, where the choice of technology is based on factors including Surface-modified carbon nanotubes improve heavy metal adsorption by increasing total solids (TSs), volatile solids (VSs), chemical oxygen demand (COD), and particularly designed solutions for certain problems. Likewise, wastewater that contains cyanide and metal complexes runs through a single, painstakingly planned and executed oxidation step with a chlorine solution and an alkaline reagent. Anaerobic and aerobic systems for treating organic wastewater are gaining popularity, particularly low-energy anaerobic technologies, due to their low cost and environmental benevolence. To overcome these abecedarian limits, a variety of strategies have been employed, including membrane-grounded procedures similar as ion exchange, electrochemical treatment, adsorption, natural treatment, Fenton processes, coagulation, flocculation, and UV- grounded processes.

Indeed though these ultramodern approaches give promising results for removing poisons from wastewater, it's critical to identify and address the remaining challenges and limitations associated with their application. new wastewater treatment technologies include ozone product via water electrolysis or nimbus discharge, electrocoagulation, mongrel ways, nanotechnology, and membrane technology. These procedures are primarily designed to remove dangerous pollutants and venoms from wastewater, similar as bacteria, contagions, heavy essence, medicinals, hormones, artificial colors, and honey retardants. This process employs a variety of physical, chemical, and natural processes, including membrane filtration, adsorption, coagulation- flocculation, solvent birth, ion exchange, photodegradation, catalytic oxidation, electrochemical oxidation, and rush. This process employs a variety of physical, chemical, and natural processes, including membrane filtration, adsorption, coagulation- flocculation, solvent birth, ion exchange, photodegradation, catalytic oxidation, electrochemical oxidation, and rush. Several pollutants have been successfully excluded exercising nanoparticles in these ways. Still, because these technologies consume a lot of energy, they can be precious. The ultimate thing is to develop wastewater treatment installations able of effectively and fully removing arising pollutants (ECs). Current exploration aims to increase the efficacity, sustainability, and effectiveness of colorful remedy ways. A wastewater treatment technology that seamlessly mixes biological treatment with aerobic microorganisms and ozone sterilization has been created as a result of innovative efforts. Even though these technologies show a lot of promise for cleaning wastewater and reducing toxins, it's crucial to understand [20].

3.2 Reducing the environmental effects of wastewater

Even though earlier studies have not sufficiently addressed the environmental effects of wastewater, more people need to be made aware of the issue so they may comprehend the necessity for wastewater treatment.

3.3 Sustainable cities and communities

By guaranteeing that there's an acceptable force of water to fulfill the constantly growing demands of civic areas, wastewater treatment helps to make sustainable metropolises. The goal of wastewater treatment is to optimize water supply, particularly in underserved areas like informal settlements. Human activity currently uses more than half of all available water runoff. About 90% of all water use is for industrial uses, and less than 10% is for residential ones. Even though families use the least amount of water, they have a big influence on water conservation. Households can help reduce water consumption and encourage conservation initiatives outside of their own premises by adopting water-saving practices and techniques within their homes. The fastest-growing industry is anticipated to be household water use, which is predicted to rise by more than 80%.

3.4 Challenges in wastewater treatment and future opportunities

The use of slice- edge wastewater treatment technology is fraught with socioeconomic issues in both the USA and Africa. Common obstacles include a lack of funding, conflicting agendas, and the requirement for infrastructure development. Common issues include addressing socioeconomic inequities, guaranteeing equitable access, and overcoming opposition to change. Opportunities to improve wastewater management arise from innovation in socioeconomic areas. Opportunities exist in the USA in creating funding models that address affordability issues for underserved communities, promote private sector participation, and provide incentives for sustainable practices. Opportunities for equitable and sustainable wastewater management techniques can be unlocked in Africa by adopting decentralized, nature-based solutions that are in line with regional socioeconomic circumstances. To achieve the intended results and avoid any mishaps, the wastewater treatment factory also requires real-time monitoring. With inadequate staff, the wastewater treatment factory may struggle to give real- time monitoring. One of the main tactics employed by wastewater treatment facilities to offer round-the-clock monitoring and prompt interventions is the automation of operations using technology.

4. Conclusions

The environmental sustainability of wastewater treatment technologies offers a promising pathway toward achieving water and resource security, mitigating environmental degradation, and addressing global water scarcity. The potential benefits, such as water reuse, resource recovery, and reduced environmental impacts, are significant and align with global goals of sustainability and circular economy principles. Environmentally sustainable wastewater treatment Technology can play an important part in attaining sustainable water management, contributing to both original and global environmental sustainability goals. Wastewater Treatment technologies are essential for maintaining ecosystems, safeguarding public health, and efficiently managing water resources. Over the past few years, the emphasis on environmentally sustainable wastewater treatment has grown significantly, driven by the increasing need to reduce environmental impacts, conserve water resources, and address the growing demand for wastewater reuse.

The review of sustainable wastewater treatment technologies highlights several key benefits and challenges:

Key Benefits:

1. **Water Reuse and Resource Recovery**: Sustainable technologies, such as membrane filtration and constructed wetlands, can recover water and valuable resources like nutrients (nitrogen and phosphorus) and biogas, which can be repurposed for agricultural or industrial use, reducing reliance on fresh water sources.
2. **Energy Efficiency and Greenhouse Gas Mitigation**: Many advanced wastewater treatment processes focus on energy recovery, such as biogas production through anaerobic digestion, and reducing energy consumption, thus contributing to lower operational costs and reduced carbon footprints.
3. **Minimal Chemical Usage and Toxic Byproducts**: Natural and biological treatment methods, including constructed wetlands and aerobic processes, reduce the need for chemicals, minimizing chemical waste and lowering the risk of introducing harmful pollutants into the environment.
4. **Enhanced Ecosystem Health**: Certain sustainable technologies, such as constructed wetlands, not only treat wastewater but also provide valuable ecosystems, supporting biodiversity and enhancing local environmental quality.

Key Challenges:

1. **High Capital and Operational Costs:** Advanced sustainable wastewater treatment technologies often come with high initial capital investment and operational expenses, which can be a barrier for smaller municipalities or developing countries to implement.
2. **Energy Demands and Operational Complexity:** Technologies like reverse osmosis and membrane bioreactors can be energy-intensive and require skilled technical expertise for operation and maintenance, posing challenges in areas with limited resources.
3. **Sludge Management and Disposal:** Efficient sludge management remains a significant challenge. While some technologies help in resource recovery, the disposal or further treatment of residual sludge can still generate environmental risks if not properly managed.
4. **Public Perception and Acceptance:** The acceptance of treated wastewater, particularly for potable reuse, faces resistance in some communities, necessitating public education and trust-building efforts to overcome societal reluctance.
5. **Regulatory and Policy Gaps:** Inconsistent or inadequate regulatory frameworks can hinder the development and widespread adoption of sustainable wastewater treatment technologies. Clearer policies, regulations, and incentives are necessary to encourage the integration of water reuse and resource recovery practices.

The review highlights how crucial it is to manage wastewater sustainably using cutting-edge methods and technologies. Improvements in resource conservation, sophisticated purification techniques, and operational efficiency have resulted from developments in smart water management utilizing AI, IoT, and nanotechnology. Algae-based treatment systems are emphasized as promising approaches for biomass production, organic pollutant degradation, and nutrient removal that may find use in industrial, municipal, and agricultural contexts. These technologies improve resource recovery and nutrient removal while using less energy than traditional techniques like membrane bioreactors and activated sludge. By integrating cutting-edge technologies, wastewater is positioned as a significant resource for reuse, carbon sequestration, and ecosystem restoration, ensuring public health protection, environmental preservation, and sustainable water resource management.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

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All relevant data and supporting information are included in the article, thus there is no need to consult external sources for more information.

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