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Innovative Approaches in Wastewater Management: A Comprehensive Review

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ABSTRACT

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The increasing depletion of freshwater resources, driven by agricultural expansion and industrial pollution, has intensified the need for wastewater reuse. However, untreated wastewater contains harmful contaminants, including heavy metals and pathogens, which threaten soil health, crop safety, and ecosystem stability. Implementing effective treatment methods is crucial to minimize these risks and ensure safe agricultural application. Various technologies physical, chemical, and biological can remove up to 99% of pollutants, but their sustainability differs. Chemical treatments, while efficient, generate hazardous by-products, whereas physical methods require high energy and produce excessive sludge. Biological treatments, leveraging microbial activity, present a cost-effective and environmentally sustainable alternative, though they necessitate precise operational control to maintain efficiency. Optimizing wastewater treatment strategies is essential to balance agricultural productivity, resource conservation, and environmental safety. Sustainable approaches should integrate advanced, eco-friendly technologies to enhance water reuse while minimizing ecological impact.

Introduction

Freshwater constitutes only 3% of Earth's water resources. However, population growth, intensified agriculture, and climate variability have disrupted freshwater availability. Water consumption is projected to exceed population growth, worsening scarcity. Industrial and urban wastewater further degrades water quality, posing ecological and health risks (Smith *et al.,* 2021). Wastewater, though a concern, can be a valuable resource, especially in arid regions. Rich in nutrients, it supports agriculture, but contaminants like heavy metals and pathogens pose hazards. Untreated use degrades soil, harms crops, and risks human health. Advanced treatment can mitigate these dangers, making wastewater a sustainable option (Johnson *et al.,* 2020).

Wastewater treatment, involving at least secondary-level disinfection, expands water resources for agriculture and industry (Taylor *et al.,* 2019). Treated wastewater reduces reliance on freshwater and chemical fertilizers due to its nutrient content (Martinez *et al.,* 2022). However, ensuring microbiological and chemical safety remains a critical challenge, requiring continued research and innovation (Anderson *et al.,* 2021).

Various techniques are employed to reduce contaminants in wastewater, classified into physical, chemical, and biological methods. Each approach has advantages and limitations concerning cost, efficiency, environmental impact, pre-treatment needs, and byproduct generation. Among these, biological treatment is more environmentally friendly, requires less land, and has lower capital costs (Luo *et al.,* 2014; Verma *et al.,* 2017). Biological wastewater treatment relies on microorganisms to break down organic matter, reducing biochemical oxygen demand (BOD). This process utilizes natural microbial metabolism to oxidize and remove soluble organic substances under suitable conditions (Hedaoo *et al.,* 2012; Wang *et al.,* 2019). Additionally, biological treatment eliminates total nitrogen and phosphorus while also removing suspended and dissolved substances, including organic matter and inorganic ions such as calcium, potassium, sulfate, nitrate, and phosphate (Metcalf & Eddy, 2003; Sharma *et al.,* 2021).

Despite its advantages, biological treatment is a slow process and may promote the growth of unwanted microorganisms that interfere with treatment efficiency (Gupta & Yadav, 2020). Given the significance of wastewater management, physical, biological, and chemical methods are critically analyzed to determine the most effective and sustainable techniques. This review aims to examine challenges and opportunities in wastewater treatment while providing a comparative analysis to guide future research toward innovative and cost-effective approaches (Zhou *et al.,* 2022).

Hazards of direct application of wastewater for agricultural purpose

Globally, approximately 20 million hectares of agricultural land rely on wastewater irrigation, reducing pressure on freshwater resources (Gökçeku *et al.,* 2023; Mateo-Sagasta *et al.,* 2017). However, untreated wastewater use, particularly in low-income regions of Asia, Africa, and Latin America, poses serious risks to ecosystems, biodiversity, and food safety (Kesari *et al.,* 2021; Drechsel *et al.,* 2015).

Industrial effluents from paper, textile, leather, and dyeing industries introduce hazardous contaminants that degrade natural resources and disrupt ecological balance (Jan *et al.,* 2023; Raschid-Sally & Jayakody, 2008).

Exposure to these pollutants threatens the health of farmers, agricultural workers, and consumers, necessitating stringent wastewater management strategies (Qadir *et al.,* 2010; Singh & Agrawal, 2018). Effective treatment and regulation are essential to mitigate environmental and public health risks while promoting sustainable water reuse practices. Different major hazards of waste water demonstrate in table 1.

Untreated wastewater severely impacts soil productivity, causing salinity, land sealing, and structural degradation due to sodium accumulation, leading to erosion (Qadir *et al.,* 2010; Rengasamy, 2018). Excess salts reduce permeability, hinder nutrient uptake, and alter soil properties, ultimately reducing crop yields (Mainardis *et al.,* 2022; Singh & Agrawal, 2018; Sharma *et al.,* 2021). Long-term use exacerbates soil degradation, threatening sustainable agriculture and necessitating improved wastewater management (Mateo-Sagasta *et al.,* 2017; Raschid-Sally & Jayakody, 2008).

Pathogenic effect

Wastewater irrigation poses serious health risks due to pathogenic contaminants, including bacteria, viruses, and parasitic worms, which infiltrate the food chain and negatively impact surrounding communities (Ahmid *et al.,* 2023; Qadir *et al.,* 2010; Toze, 2006). Contaminated soils act as reservoirs for intestinal parasites such as helminths, nematodes, and tapeworms, which are responsible for severe health conditions, including anemia, cognitive impairments, and behavioral disorders (Kesari *et al.,* 2021; Bos *et al.,* 2010; Drechsel *et al.,* 2015). Additionally, exposure to heavy metals and pharmaceutical residues in wastewater can contribute to long-term health complications, including organ damage and antimicrobial resistance (Mateo-Sagasta *et al.,* 2017; Zhang *et al.,* 2019).

Long-term exposure to these pathogens increases the risk of chronic infections, weakening immune responses and reducing overall public health standards. Consequently, the use of untreated wastewater in agriculture remains a major concern, highlighting the urgent need for effective treatment and management strategies to ensure food safety and environmental sustainability. Various diseases and pathogens are illustrated in Fig 2 and table 2.

Heavy metals effect

Wastewater contains varying concentrations of heavy metals such as lead, cadmium, mercury, iron, and copper, leading to soil contamination and bioaccumulation in crops, posing significant health and ecological risks (Chaoua *et al.,* 2019; Alghobar *et al.,* 2014; Wuana & Okieimen, 2011). Heavy metals leach into groundwater, degrade soil health, and threaten aquatic ecosystems through runoff and erosion (Tytla, 2019; Ofori *et al.,* 2021; Khan *et al.,* 2022). They also suppress microbial activity, reduce enzymatic functions, and induce oxidative stress in plants, impairing photosynthesis, respiration, and nutrient uptake, which can result in total crop failure (Abdel-Rahman, 2021; Feszterova *et al.,* 2021; Alengebawy *et al.,* 2021; Hu *et al.,* 2021; Nino-Savala, 2019). Effective wastewater treatment and remediation strategies are crucial to mitigating these risks (Rizwan *et al.,* 2017; Gupta *et al.,* 2020).

Health effect

Wastewater contamination poses severe health risks through polluted drinking water, food chain accumulation, and pathogen transmission (Ungureanu *et al.,* 2020; Chen *et al.,* 2013). Persistent contaminants like heavy metals exacerbate these threats, leading to bioaccumulation and biomagnification (Chaoua *et al.,* 2019; Mahmood & Malik, 2014). Wastewater exposure is linked to diseases such as osteoporosis, kidney disorders, cholera, hepatitis A, and helminth infections (WHO, 2006; Xiao *et al.,* 2017; Mishra *et al.,* 2023). In Japan, cadmium-contaminated irrigation has contributed to osteoporosis, while helminth exposure causes anemia and cognitive impairments (Bos *et al.,* 2009; Tariq & Mushtaq, 2023).

Agricultural workers face additional risks of skin infections and dermatitis (Gupta *et al.,* 2020; Ofori *et al.,* 2021). Effective wastewater treatment and rigorous risk assessment are crucial to preventing these public health hazards (Rizwan *et al.,* 2017; Khan *et al.,* 2022).

Groundwater Contamination

Groundwater serves as a primary irrigation source, particularly in water-scarce regions. However, increasing contamination risks stem from excessive agrochemical use, industrial discharge, municipal waste, and heavy metal accumulation (Tariq & Mushtaq, 2023). Wastewater remains a major contributor to groundwater pollution, though contamination causes vary globally.

In developing countries, poor sanitation and overpopulation accelerate groundwater degradation (Abanyie *et al.,* 2023), whereas excessive agrochemical application in rural areas of developed nations poses significant threats (Mello *et al.,* 2023).

Urban groundwater pollution primarily results from industrial and domestic waste containing chemical pollutants and pathogenic microorganisms (Abanyie *et al.,* 2023). Contaminants infiltrate groundwater via seepage losses, well cross-contamination, and infiltration of polluted water (Pradhan *et al.,* 2023), posing severe health risks to humans and animals through direct or indirect exposure (Singh *et al.,* 2014; Kumar *et al.,* 2022).

Various wastewater treatment approaches

The search for cost-effective and efficient wastewater treatment technologies remains a priority due to the limitations of conventional methods. Existing approaches focus on pollutant removal and ecosystem protection through primary, secondary, and tertiary treatments.

The tertiary stage achieves up to 99% contaminant removal, producing high-quality water suitable for reuse (Gupta *et al.,* 2012; Saravanan *et al.,* 2021).

Chemical Approaches

Coagulation

Coagulation destabilizes contaminants using chemical agents, aiding in the removal of suspended solids, chromaticity, and hazardous compounds.

It improves the biodegradability of pharmaceutical effluents but remains ineffective against dissolved organic waste (Bratby, 2016; Jagaba *et al.,* 2023).

Crystallization

A solid-liquid separation technique, crystallization removes soluble impurities by evaporation, cooling, or solvent addition, making it effective for high-TDS wastewater (Gupta *et al.,* 2012; Samer, 2015).

Solvent Extraction

This method dissolves pollutants using organic solvents like acetone, hexane, and benzene, effectively removing oils, greases, and some metal ions (Gupta *et al.,* 2012; Saravanan *et al.,* 2021).

Oxidation

Chemical oxidation degrades pollutants into biodegradable compounds using oxidizing agents such as ozone, chlorine, and Fenton's reagent. It is effective for ammonia, phenols, hydrocarbons, and dyes (Samer, 2015; Saravanan *et al.,* 2021).

Chemical Precipitation

This technique eliminates heavy metals by converting them into insoluble forms. Despite its high efficiency, it generates large volumes of sludge requiring disposal (Son *et al.,* 2020; Tanong *et al.,* 2017).

Ion Exchange

Ion exchange replaces toxic ions with non-toxic counterparts using synthetic or natural resins. It allows for dye recovery but is costly and limited to small-scale applications (Nahiun *et al.,* 2021; Saravanan *et al.,* 2021).

Flocculation

Flocculation precipitates heavy metals and removes color contaminants, turbidity, and fine particles. However, its complexity and disposal challenges limit large-scale application (Nahiun *et al.,* 2021; Saravanan *et al.,* 2021).

Adsorption

Adsorption binds contaminants to porous materials like activated carbon and nanomaterials. Cost-effective and widely applicable, its selectivity and adsorbent disposal remain challenges (Manikandan & Saravanan, 2018; Prasannamedha *et al.,* 2021).

Advanced Approaches

Membrane Bioreactor (MBR)

MBR integrates biological treatment with membrane filtration, offering superior effluent quality, reduced sludge production, and high organic removal efficiency. However, energy costs, membrane fouling, and maintenance remain concerns (Iorhemen *et al.,* 2016; Waqas *et al.,* 2023).

Advanced Oxidation Processes (AOPs)

AOPs utilize hydroxyl radicals to break down persistent organic and inorganic pollutants via UV, ozone, and photocatalysis. AOPs are highly effective but require high energy inputs and precise operational control (Wang & Xu, 2012; Giannakis *et al.,* 2021).

Ozonation

Ozone oxidizes organic contaminants through direct electrophilic reactions and hydroxyl radical formations. It reduces sludge and degrades persistent pollutants, but ozone instability limits its widespread application (Rekhate & Srivastava, 2020; Hone & Kappe, 2020).

Ozonation with UV Radiation (O3/UV)

Combining ozone with UV enhances pollutant breakdown by accelerating radical formation. This hybrid method is particularly effective for dye removal and recalcitrant organic pollutants (Rekhate & Srivastava, 2020; Pillai *et al.,* 2009).

Electrocoagulation (EC)

EC employs electrodes to induce coagulation, eliminating the need for chemical additives. It effectively removes heavy metals and suspended solids, though electrode maintenance increases costs (Garcia-Segura *et al.,* 2017; Dant *et al.,* 2023).

Electrocoagulation-Flotation (ECF)

ECF enhances EC by using hydrogen bubbles to float pollutants for easy removal. Effective for diverse wastewater types, it reduces chemical usage but requires electrode replacement and energy input (Mousazadeh *et al.,* 2021; Othmani *et al.,* 2022).

Nanotechnology

Nanoparticles (Ag, TiO2, CNTs) enhance adsorption, catalysis, and pollutant degradation. Carbon-based nanomaterials and metal oxides exhibit strong antimicrobial properties, but long-term ecological impacts require further study (Bethi *et al.,* 2016; Vallinayagam *et al.,* 2021).

Ultrasound Treatment

Ultrasound disrupts microbial cells and degrades contaminants through cavitation, providing a chemical-free alternative for water purification. Operational expertise is essential for effective implementation (Tijani *et al.,* 2014; Zupanc *et al.,* 2019).

Wastewater Treatment via Solar Energy

Solar-driven water treatment utilizes solar stills and photovoltaic (PV) energy to facilitate distillation. Solar stills convert solar radiation into heat, evaporating water in a distillation chamber, followed by condensation and collection (Ugwuishiwu *et al.,* 2016). Alternatively, PV panels generate electricity to power distillation systems, enabling off-grid operation (Sharon & Reddy, 2015).This eco-friendly approach minimizes reliance on fossil fuels and provides sustainable water for industrial and agricultural use. However, challenges include low wateryield**,** large space requirements**,** and climate dependency. Hybrid integration with other power sources can enhance efficiency but increases operational costs (Tiwari & Tiwari, 2008; Qasim *et al.,* 2019). Different advance techniques describes in table 4.

Biological waste water treatment

Overview

With a growing population and limited freshwater resources**,** sustainability of natural systems is at risk. Dispose of water after a single use not only deplete reserves but also pollutes the environment**.** While advanced treatment methods such as advanced oxidation, membrane bioreactors (MBRs), UV radiation, and nanotechnology effectively remove contaminants, they often come with high energy demands and environmental concerns**.** Similarly, chemical treatments, though effective, contribute to secondary pollution and are economically unsustainable**.**

In contrast, biological wastewater treatment offers a cost-effective and eco-friendly alternative, utilizing microorganisms (bacteria, fungi, algae, protozoa) and plants to naturally break down organic and inorganic pollutants via biosorption and biodegradation (Akpor *et al.,* 2014; Roy & Saha, 2021). These microbial communities thrive by consuming waste materials as a source of nutrition and energy, making them a natural solution for wastewater purification (Gupta *et al.,* 2017). Additionally, microalgae-based treatment not only removes pollutants but also produces valuable byproducts such as biofuels and bioplastics**.** Their high adaptability, rapid growth, and ability to function under diverse environmental conditions make them an ideal candidate for large-scale wastewater treatment (Pooja *et al.,* 2022; Hussain *et al.,* 2021). By integrating biological treatment with other sustainable technologies, wastewater can be efficiently recycled, reducing the strain on natural water reserves and promoting a circular economy**.**

A list of different microbial species is given in table 5 along with their targeted waste and treatment efficacies.

Microbial wastewater treatment is recognized as a cost-effective, sustainable, and environmentally friendly alternative to physical and chemical treatment methods (Adin & Asano, 1998; Gude, 2016; Tchobanoglous *et al.,* 2003; Metcalf & Eddy, 2014). Fats, oils, and greases (FOG) in wastewater often exhibit complex structural properties and are typically retained as sludge after treatment (Salama *et al.,* 2019; Kim *et al.,* 2021). However, microbial treatment plays a crucial role in the degradation of FOG and the mitigation of associated gaseous emissions (Wang *et al.,* 2019; Zinder, 1993).

This method is particularly effective in removing a variety of pollutants, including heavy metals, organic waste, and pathogenic microorganisms (Akpor *et al.,* 2014; Wu *et al.,* 2019). Furthermore, the mineralization of organic matter by microbial communities not only ensures water safety but also enhances the utility of sludge as a nutrient source. Additionally, microbial processes such as ammonia oxidation to nitrite and nitrate, denitrification, and biological phosphorus removal contribute significantly to wastewater purification (Rahimi *et al.,* 2020; Seviour & Nielsen, 2010).

Microbial Treatment Process

Microbial treatment systems optimize the natural decomposition of contaminants in industrial wastewater by enhancing microbial activity (Saravanan *et al.,* 2021; Nancharaiah *et al.,* 2016). Aerobic treatment systems utilize microorganisms such as protozoa and oxygen-dependent bacteria (Imwene *et al.,* 2022; Bitton, 2010). These microbes can be naturally present or deliberately introduced into the system (Roszak & Colwell, 1987; Curtis *et al.,* 2002). Oxygen is a crucial component in aerobic microbial treatment, facilitating the oxidation and degradation of organic matter (Gallert & Winter, 2005; Rittmann & McCarty, 2012). To maintain optimal microbial function, oxygen is supplied via surface aerators or diffusers (Garcia-Ochoa *et al.,* 2010; Tchobanoglous *et al.,* 2014). The biological oxygen demand (BOD) serves as an indicator of pollutant degradation efficiency (Jouanneau *et al.,* 2014; APHA, 2017).

The organic contaminants in wastewater serve as substrates for microbial metabolism (Zheng *et al.,* 2013; Cydzik-Kwiatkowska & Zielinska, 2016). Through aerobic respiration, microorganisms convert complex organic compounds into simpler, more stable byproducts, forming microbial biomass composed of non-decomposable materials and dead microbial cells (Jenkinson & Ladd, 1981; Bhatia *et al.,* 2018). Clarification follows microbial treatment, where biomass aggregates into sludge and settles at the bottom (Asthana *et al.,* 2017; Spellman, 2018).

This separation process, occurring in secondary settling tanks or clarifiers, produces a more refined effluent (Truu *et al.,* 2009; Wei *et al.,* 2003). The sludge, enriched with microbial biomass and solid residues, undergoes further processing such as dewatering to reduce volume and enhance stability (Ahmad *et al.,* 2022; Wilén *et al.,* 2006). Aerobic microbial treatment effectively removes organic pollutants, allowing the treated water to be either safely discharged or subjected to additional treatment (Michael-Kordatou *et al.,* 2015; Tchobanoglous *et al.,* 2014).

Biological Wastewater Treatment Technologies

Activated Sludge Process

The activated sludge process begins with wastewater collection in an aeration tank, where suspended aerobic bacteria decompose organic matter (Kayser, 2005; Jenkins *et al.,* 2003). The decomposed material aggregates into flocs that settle in a secondary tank, where sedimentation separates suspended flocs, while excess solids are removed as sludge (Wang *et al.,* 2009; Asiwal *et al.,* 2016; Grady *et al.,* 2011). Some activated sludge is recirculated into the aeration tank to maintain microbial populations. This method has low capital and operational costs but presents challenges related to sludge disposal (Prabu *et al.,* 2011; Andreottola *et al.,* 2009).

Fixed Bed Bioreactors (FBBRs)

FBBRs consist of multiple chambers filled with porous media such as plastic, foam, or ceramic, providing a large surface area for microbial biofilm formation (Jaibiba *et al.,* 2020; Ødegaard, 2006). These reactors include both aerobic and anoxic chambers to facilitate simultaneous denitrification and carbonaceous removal. Microbial biofilms in different compartments target specific pollutants through processes such as denitrification, sulfide reduction, nitrification, and anammox (Benthack *et al.,* 2001; Lackner *et al.,* 2014). Additionally, this method produces minimal sludge.

Membrane Bioreactors (MBRs)

MBRs integrate membrane filtration with conventional suspended growth bioreactors, efficiently removing total suspended solids (TSS) and reducing biological oxygen demand (BOD) (Wang & Menon, 2009; Judd, 2011). These systems include anaerobic/aerobic treatment tanks, aeration systems, membrane tanks, and ultrafiltration membranes. Although highly effective, MBRs require significant capital and operational investments due to their complex design and maintenance requirements (Branch, 2016; Fraser, 2017; Drews, 2010).

Trickling Filters

Trickling filters utilize biofilm-coated media such as stone, sand, foam, or ceramic to degrade organic contaminants (Zea *et al.,* 2020; Lazarova & Manem, 2000). These systems support both aerobic and anaerobic microbial activity and are widely used in municipal wastewater treatment, particularly for odor control and hydrogen sulfide (H2S) removal (Barbusinski & Kalemba, 2016; Kiepper, 2018).

Constructed Wetlands

Constructed wetlands use natural ecosystems comprising soil, microorganisms, and vegetation to treat wastewater. Microbial activity within these systems facilitates pollutant degradation (Williams, 2002; Kadlec & Wallace, 2009). Beyond water treatment, constructed wetlands enhance biodiversity and offer recreational value. However, they are limited by slow treatment rates and location-specific constraints (Kayikcioglu, 2012; Zhang *et al.,* 2021).

Advantages of Microbial Wastewater Treatment

Organic Matter Mineralization

Microbial degradation effectively mineralizes organic matter, converting complex compounds into stable byproducts that serve as nutrients for agricultural applications (Hobson *et al.,* 1974; Diaz *et al.,* 2018).

Disinfection

Microbial treatment significantly reduces pathogen levels, especially when combined with disinfection techniques (Rose, 2005; Bitton, 2010). Although efficacy varies across different microbial treatment methods, most approaches effectively mitigate major pathogens such as hepatitis viruses (Rojas *et al.,* 2006; Sano *et al.,* 2016).

Reduced Sludge Production

Biological treatment processes play a crucial role in minimizing sludge production by promoting efficient degradation of organic matter. The implementation of anaerobic digestion further contributes to sludge volume reduction by converting biodegradable components into biogas, thereby improving waste management and sustainability (Appels *et al.,* 2008; Atelge *et al.,* 2020).

Heavy Metal and Hazardous Compound Removal

Microbial biosorption is a highly effective mechanism for the removal of toxic heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As), along with persistent organic pollutants. The efficiency of this process is largely influenced by microbial strain selection and the physicochemical properties of the contaminants. While biosorption presents a promising alternative to conventional treatment methods, its performance varies depending on environmental conditions and microbial adaptability (Devda *et al.,* 2021; Haberkamp *et al.,* 2019; Zupancic & Grilc, 2012).

Energy Efficiency

Compared to conventional chemical and physical treatment methods, microbial-based wastewater treatment exhibits superior energy efficiency. Anaerobic processes, in particular, contribute to sustainability by generating biogas as a valuable byproduct. This not only reduces energy consumption but also supports the transition toward renewable energy integration in wastewater management systems (Ahmed *et al.,* 2021).

Different types of Microbes for waste water treatment

Bacteria

Aerobic and anaerobic bacteria are vital in wastewater treatment, with selection based on wastewater type, technology, and goals. Aerobic bacteria degrade organic matter in oxygen-rich environments, requiring mechanical aeration when oxygen is low (Lee *et al.,* 2009; Jia & Yuan, 2016). They are highly effective in high-strength wastewater treatment, such as activated sludge processes (Gerardi, 2002).

Anaerobic bacteria function in anoxic conditions, breaking down sludge through anaerobic digestion, which reduces volume and produces methane for energy (Appels *et al.,* 2008). They are ideal for high-organic-content wastewater but need longer retention times and careful monitoring (Speece, 2008; Chen *et al.,* 2008). Facultative bacteria like Pseudomonas and Enterobacter adapt to both conditions, favoring oxygen-rich environments (Strobel, 2009; Madigan *et al.,* 2018). Proper strain selection optimizes treatment efficiency.

Fungi

Fungi are recognized as potential bioremediation agents for the remediation of heavy metal-contaminated environments. Among them, filamentous fungi represent a diverse group of eukaryotic organisms, encompassing molds, yeasts, and mushrooms.

The phylum Ascomycota contains a significant proportion of known filamentous fungi, including several genera with strong bioremediation potential, such as *Verticillium, Fusarium, Penicillium,* and *Aspergillus*. These fungi possess remarkable biosorption capabilities, making them effective in the removal of heavy metals from industrial effluents and wastewater (El-Bondkly & El-Gendy, 2022).

In particular, numerous *Aspergillus* strains serve as highly efficient biosorbents, capable of removing toxic metals such as cadmium from oil field waste water and copper, lead, arsenic, and chromium from aqueous solutions**.**

Their cell walls contain functional groups such as carboxyl, hydroxyl, and amino groups, which facilitate metal ion binding and adsorption (El-Bondkly & El-Gendy, 2022; Gadd, 2009). However, filamentous fungi exhibit diverse morphologies and physiological traits, which can result in both beneficial and detrimental effects.

While certain fungi contribute to effective heavy metal removal, others, particularly mold-forming species, can disrupt biological wastewater treatment processes. For instance, excessive fungal growth may impair flocculation and sedimentation**,** leading to operational inefficiencies in activated sludge systems (Akpor *et al.,* 2014; Wainwright, 2020).

The following table (Table 7) illustrates the specific capacity of different *Aspergillus* species to remove various heavy metals from wastewater.

Algal-Based Wastewater Treatment

The use of algae in biological wastewater treatment presents a promising and sustainable approach due to its potential for heavy metal sequestration, bioremediation, and biomass production (Henley, 2019). Algae, both in living and dead cell forms, have demonstrated the capacity to remove significant amounts of harmful heavy metals from wastewater through biosorption and bioaccumulation mechanisms (Goher *et al.,* 2016).

A wide range of mechanisms facilitate the remediation of heavy metals by algae, with specific pathways depending on algal species, metal type, and microclimatic conditions (Tytła, 2019).

For example, trace nutrient metals such as calcium (Ca), magnesium (Mg), copper (Cu), zinc (Zn), chromium (Cr), lead (Pb), selenium (Se), molybdenum (Mo), and cobalt (Co) are actively transported intracellularly in living algal cells via biological uptake mechanisms (Fox & Zimba, 2018).

Beyond metal sequestration, the photosynthetic nature of algae enhances sustainability by converting nutrients present in wastewater into valuable biomass, which can be further utilized for biofuel production or as feedstock for commercially significant products.

Notably, species such as Chlorella and Dunaliella can be cultivated using wastewater, offering a dual benefit of bioremediation and biomass generation (Abdel-Raouf *et al.,* 2012).

Role of Protozoa in Wastewater Treatment

Protozoa are single-celled eukaryotic microorganisms that play an essential role in wastewater treatment by improving effluent quality. The most common protozoan groups in wastewater treatment systems include amoebae, flagellates, and ciliates, collectively constituting approximately 4% of the microbial ecosystem in wastewater (Madoni, 2011). These organisms contribute significantly by ingesting free bacteria and small, unsettled flocs**,** thereby clarifying treated effluents.

Additionally, protozoan communities serve as bioindicators of sludge age and treatment efficiency (Karczmarczyk & Kowalik, 2022). Their abundance and diversity provide insights into system health and operational conditions.

- Amoebae thrive in young sludge systems, where high nutrient concentrations and limited microbial competition enable their rapid proliferation (Kusnierz *et al.,* 2022). They dominate in conditions with low dissolved oxygen (DO), high particulate matter, and sudden biochemical oxygen demand (BOD) fluctuations, demonstrating resilience to toxic shocks and stress conditions.

- Flagellates grow efficiently in early sludge age phases, outcompeting bacteria for soluble nutrients due to their faster reproduction rates (Maguire, 1971). A high flagellate count in a wastewater sample often correlates with an elevated food-to-mass (F:M) ratio, indicating an abundance of soluble nutrients (Ratsak *et al.,* 1996).

The interaction between protozoa, bacteria, and other microbial communities ensures enhanced organic matter degradation and improved treatment stability, making them indispensable components of wastewater ecosystems.

Likewise, ciliates tend to grow in healthy sludge; they act as advantageous clarifying agents and are good markers of healthy floc formation because they feed on bacteria rather than organic matter (Foissner, 2016). Ciliates presence is also advantageous in microbial based waste water treatment as they have positive role to maintain optimum population of bacteria and algae (Akpor *et al.,* 2014).

Viruses

Bacteriophages, or viruses that infect bacteria, are emerging as a sustainable and targeted approach to pathogen reduction in wastewater treatment plants (WWTPs). This method, known as phage therapy, involves using lytic bacteriophages to selectively eliminate bacterial pathogens, particularly antibiotic-resistant strains that persist despite conventional disinfection processes (Withey *et al.,* 2005; Hyman, 2019).

Phage therapy has demonstrated effectiveness in suppressing resistant *Escherichia coli* strains and other pathogenic bacteria such as *Salmonella* and *Pseudomonas aeruginosa* in wastewater treatment systems (Latz *et al.,* 2016; Colavecchio *et al.,* 2017). By reducing the bacterial load, phages contribute to overall effluent safety and environmental health. Additionally, the application of bacteriophages has been shown to mitigate issues related to sludge bulking and foaming, which can interfere with wastewater treatment efficiency (Shivaram *et al.,* 2023).

Beyond pathogen control, phage-based biocontrol strategies align with circular economy principles by facilitating the reuse and safe discharge of treated wastewater (Nayak *et al.,* 2021).

Compared to chemical disinfectants, phages offer a biodegradable, self-replicating, and host-specific alternative that minimizes ecological impact while enhancing process sustainability (Fu *et al.,* 2010; Khan *et al.,* 2022).

Effect of biologically treated wastewater on soil health and overall agro-ecosystem

Impact on soil

Nutrients supply

The increasing demand on agricultural systems for food production, combined with inefficient nutrient utilization and the associated environmental pollution, has necessitated the adoption of resource-efficient strategies. The reliance on inorganic fertilizers alone is unsustainable; thus, the use of recycled wastewater, enriched with microbial activity, presents an environmentally viable alternative that enhances soil fertility (Aczel, 2019). Biologically treated wastewater serves as a dual-purpose irrigation medium, not only supplying essential nutrients but also facilitating their bioavailability through microbial-mediated mineralization processes (Quemada *et al.,* 2016).

Sustainable wastewater irrigation practices significantly enrich the soil with both macronutrients and micronutrients. The composition of wastewater varies based on its source but generally contains substantial amounts of nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) (Qadir & Scott, 2010).

Long-term irrigation with treated wastewater has been shown to markedly influence soil nutrient composition. For instance, Ganjegunte *et al.,* (2017) reported a 70-85% increase in soil nitrate concentrations due to prolonged exposure to biologically treated wastewater. Similarly, potassium concentrations exhibited a 70% enhancement, alongside improved phosphorus solubility and uptake (Bedbabis *et al.,* 2014).

Furthermore, micronutrient levels, including essential trace elements, demonstrated significant improvements in soils irrigated with treated wastewater (Galavi *et al.,* 2010; Singh *et al.,* 2012).

Table.1 Major hazards of wastewater on soil properties

Hazard	Soil properties affected	References
Soil salinization	Degrades soil structure, reduces soil permeability, as well as crop yields due to its toxic and osmotic effects	(Shakir *et al*., 2017)
Reduced soil porosity	Excess amount of sodium can cause physical problems of soil and reduces soil porosity and permeability (if its concentration rises to above 15% of the cation exchange capacity of the soil).	(Mainardis *et al*., 2022)
Water repellency	A phenomena of soil hydrophobicity occurs which leads to the soil water repellency.	(Abegunrin *et al*., 2016).
Reduced soil infiltration and hydraulic conductivity	Water infiltration into the soil and hydraulic conductivity is decreased by clogging the pores of soil at the surface with suspended materials.	(Gharaibeh *et al*., 2016)
High bulk density	The bulk density of soil irrigated with wastewater decreases because of the formation of soil aggregates.	(Mirzaei-Takhtgahi *et al*., 2018; Andrews *et al*., 2016)
Heavy metal contamination	Wastewater increases the amount of heavy metals in soil	(Rusanescu *et al*., 2022)
Ground water pollution	Ground water becomes polluted due to wastewater contaminations.	(Duenas-Moreno *et al*., 2022)

Table.2 Microorganisms present in wastewater and their effects on human health (European Commission, 2022).

Pathogen	Examples	Examples of Diseases for Humans	Reference Pathogen (Indicator)
Bacteria	*Salmonella*	Gastroenteritis (diarrhea, vomiting, fever)	*E. coli*
	Vibrio cholera	Cholera	
	Pathogenic E. coli	Gastroenteritis and septicemia	
Protozoa	*Entamoeba*	Amebiasis	*Cryptosporidium*
	Giardia	Gastroenteritis	
	Cryptosporidium	Diarrhea, fever	
Helminths	*Ascaris*	Ascariasis	Intestinal nematodes (Helminth eggs)
	Ancylostoma	Ancylostomiasis	
	Necator	Necatoriasis	
Viruses	*Enteroviruses*	Gastroenteritis, heart anomalies	*Rotavirus*
	Adenovirus	Respiratory disease, eye infection	
	Rotavirus *SARS-CoV-2 virus*	Gastroenteritis Respiratory disease	

Table.3 Major diseases attributed to wastewater irrigation

Disease	Causal organism	Route of infection	Risk order
Helminthiases, Ascariasis, Schistosomiasis, Koilonychias	Helminths (parasitic worms), intestinal nematodes, hookworm	Mainly soil contact outside home and food	High
Cholera, salmonellosis, Typhoid, Shigellosis, gastric ulcers	Bacterial infections (*Vibrio cholera, Helicobacter pylori*)	Mainly home contact and food or water	Low
Giardiasis and ameobiasis	Protozoan infections	Mainly home contact and food or water	Low
Viral gastroenteritis and infectious hepatitis	Viral infections	Mainly home contact and food or water	Least

Table.4 Advance techniques to treat waste water

Methods	Contaminants	Outcome
Ozonation	Organic contaminants in wastewater	Solublisation of sludge
UV radiation	Azo dyes from textile effluents	Degradation of stubborn dyes
Nanotechnology (metal oxide nanoparticles)	Wastewater contaminated with harmful pathogens	Antimicrobial activities
Membrane bioreactor (MBR)	municipal and industrial wastewater	Filtration
Advanced oxidation processes	organic and inorganic contaminants	breakdown of persistent organic pollutants
Ultrasound treatment	Organic contaminants	Eradication of viruses and chemical substances
Coagulation	Pharmaceutical wastewater	Elimination of suspended solids, hazardous particles

Table.5 Treated waste name

Microbial Species	Treated waste name	Effects	References
Alcaligenes faecalis	Congo red (CR) (dye)	92.51% of dye degradation rate	Eid *et al*., 2023
Alishewanella sp.	Reactive blue 59 (dye)	95% decolorization rate	Kolekar and Kodam, 2012
Staphylococcus aureus	Orange II (dye)	76% decolorization rate	Pan *et al.,* 2011
Staphylococcus hominis	Acid orange (dye)	Color removal with 94% efficiency rate	Singh *et al.,* 2014
Sludge Hammer, B. subtilis, B. laterosponus* and *P. aeruginosa	Municipal wastewater	70%, 54%, 52% and 42% reduction in synthetic wastewater respectively	Hesnawi *et al.,* 2014
Herminiimonasarsenicoxydans	wastewater	Significant absorption of arsenic from wastewater	Marchal *et al*., 2010
Lactococcus* and *Dysgonomonas	Metanil Yellow (dye)	96% color removal efficiency rate	Tian *et al*., 2019

Table.6 Common bacteria used in waste water treatments

Species	Genre	Process Involved
Achromobacter	Bacteria	Biofilters and activated sludge
Acinetobacter	Bacteria	Biological phosphorous removal
Alcaligenes	Bacteria	Biofilters, activated sludge and sludge digester
Micrococcus	Bacteria	Activated sludge and biofilters
Microtrix	Bacteria	Activated Sludge
Nitrobacter	Bacteria	Nitrification
Nitrosomonas	Bacteria	Nitrification

Table.7 Heavy metals remove through *Aspergillus* species

Pollutants (Heavy Metals)	Species Ascomycota
Cd	*Aspergillus niger*
Cu,Pb,As	*A. niger*
Cr	*A. niger, A. foetidus*
Cd	*Penicillium simplicissimum*

Figure.1 Various uses of waste water

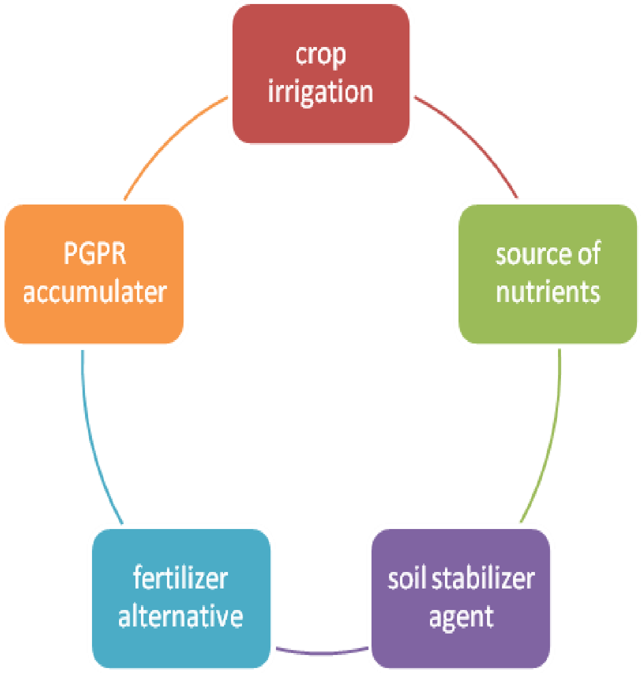


Figure.2 Pathogenic organisms causing diseases

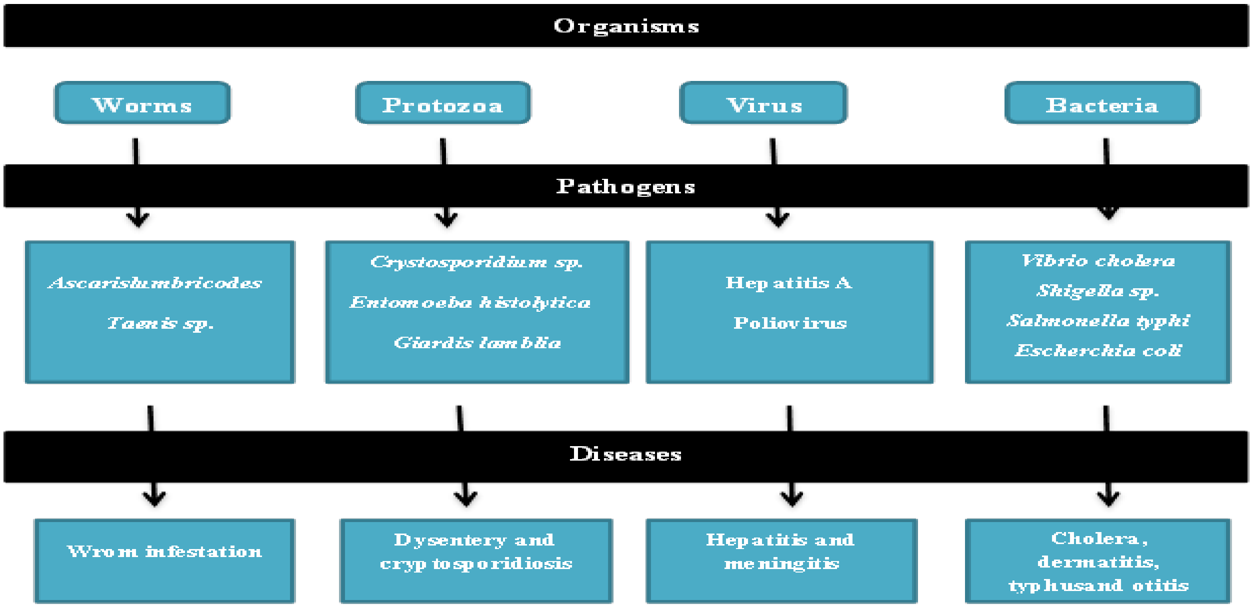


Figure.3 Pathway describing the exposure of wastewater to crops and soil, causing several diseases

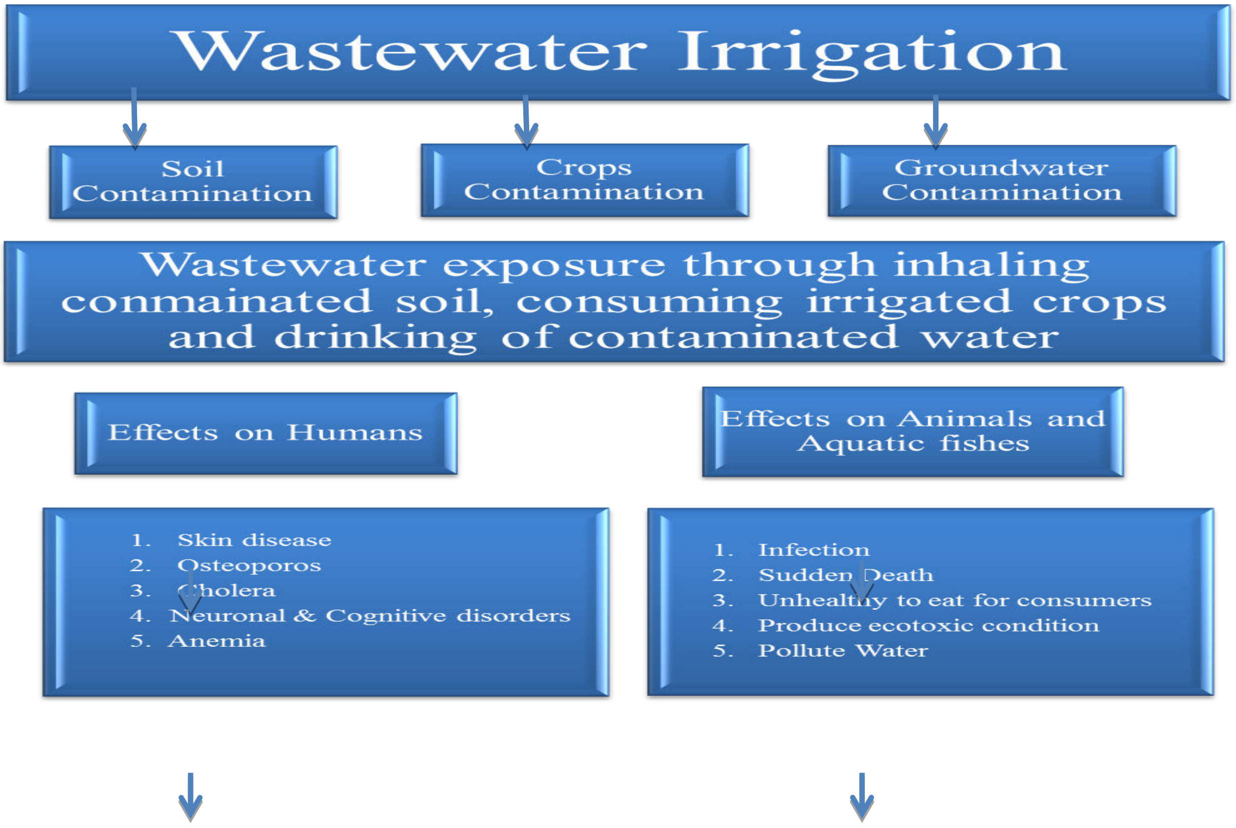


Figure.4 Ground water contamination through various resources

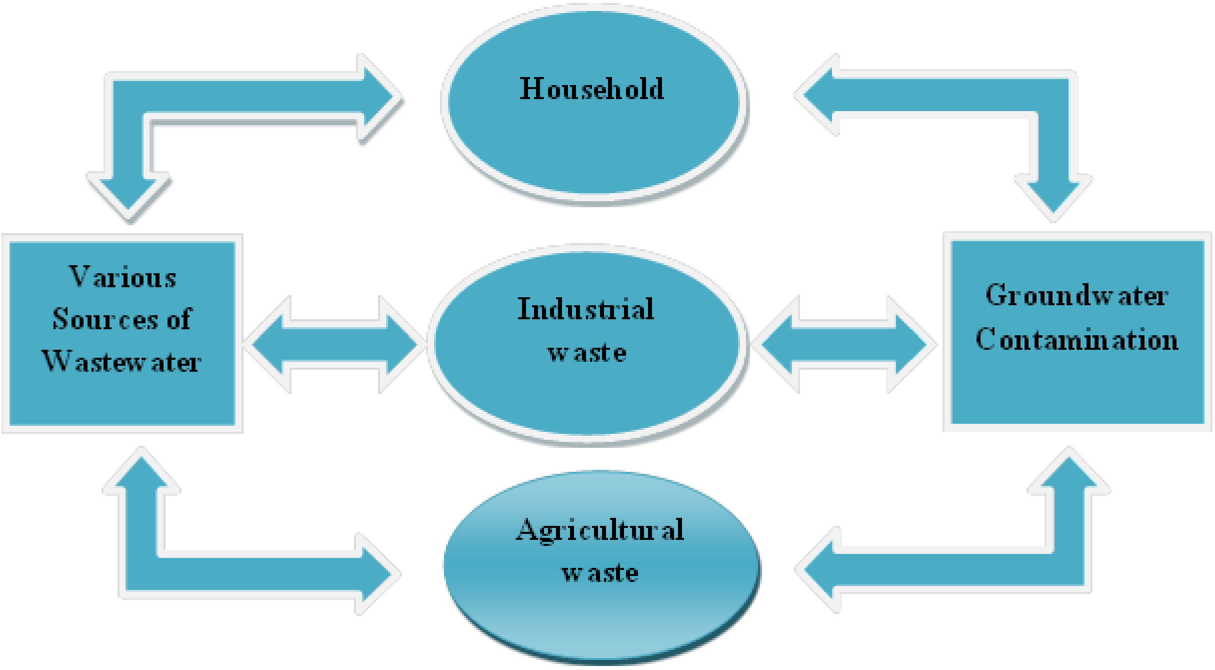


Figure.5 Biological waste water treatment

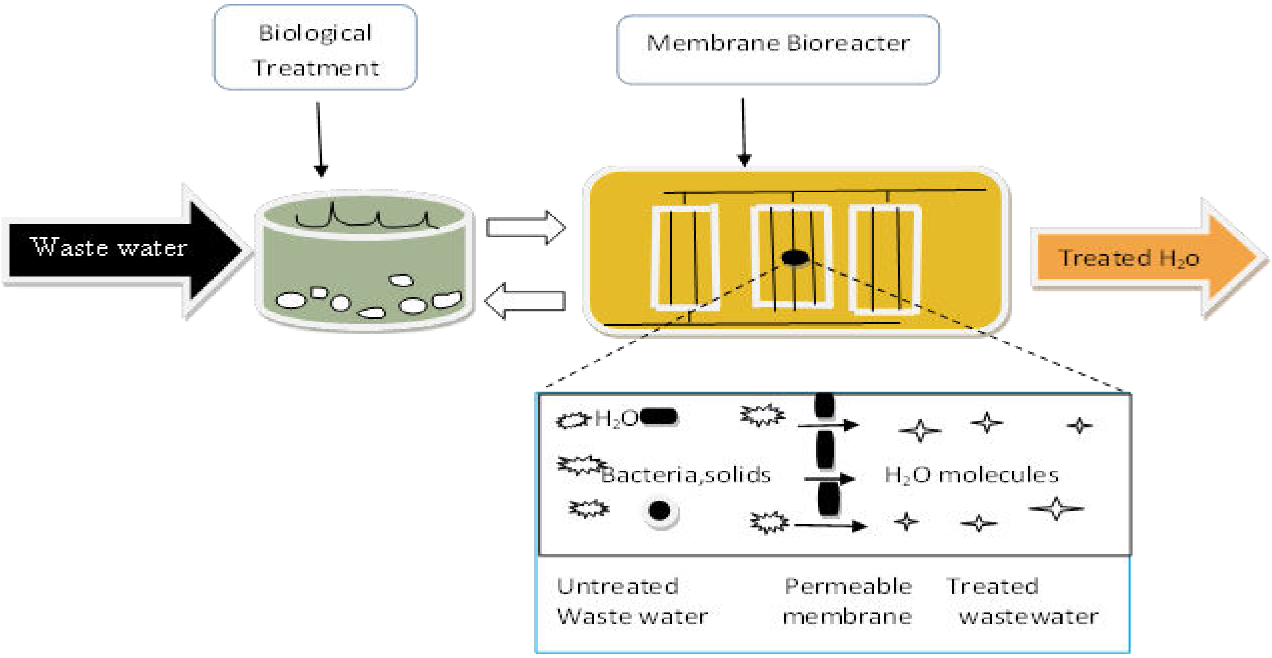


Figure.6 Role of protozoa and various species in biological wastewater treatment

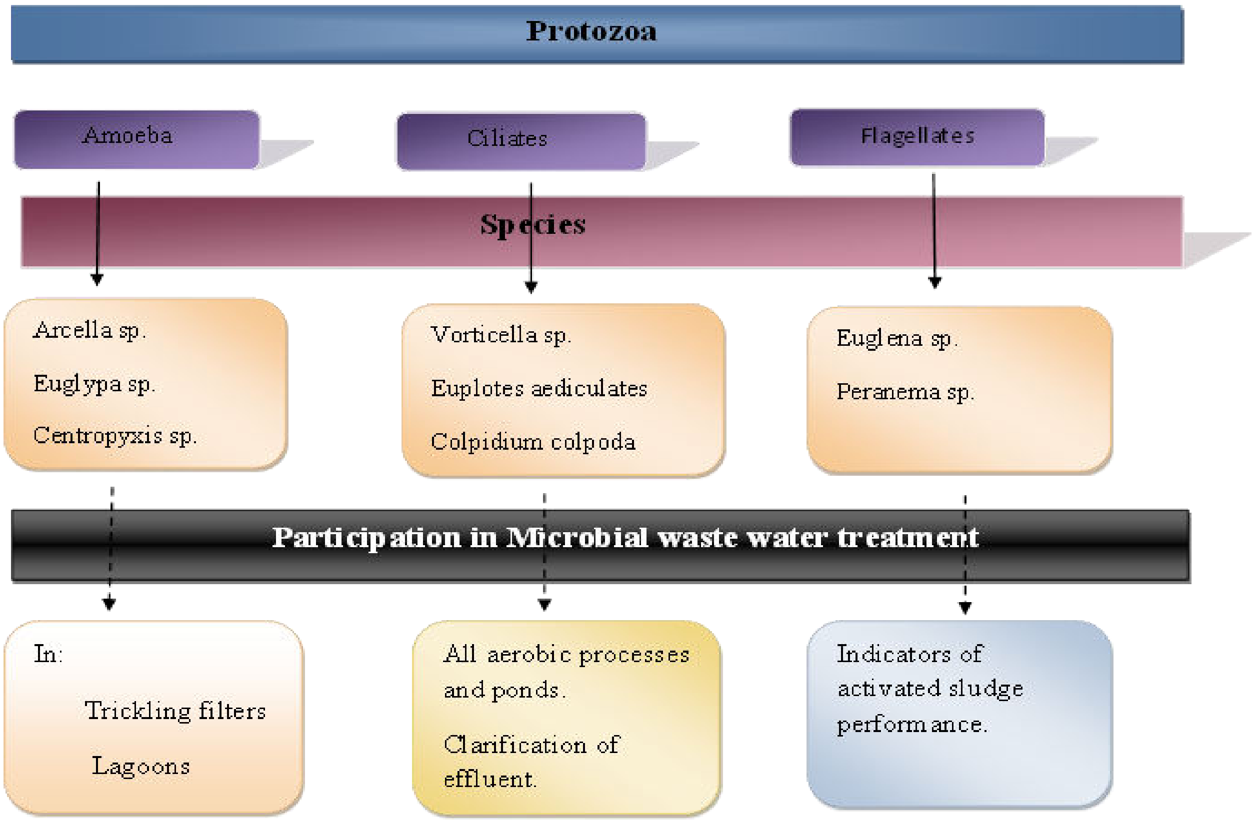
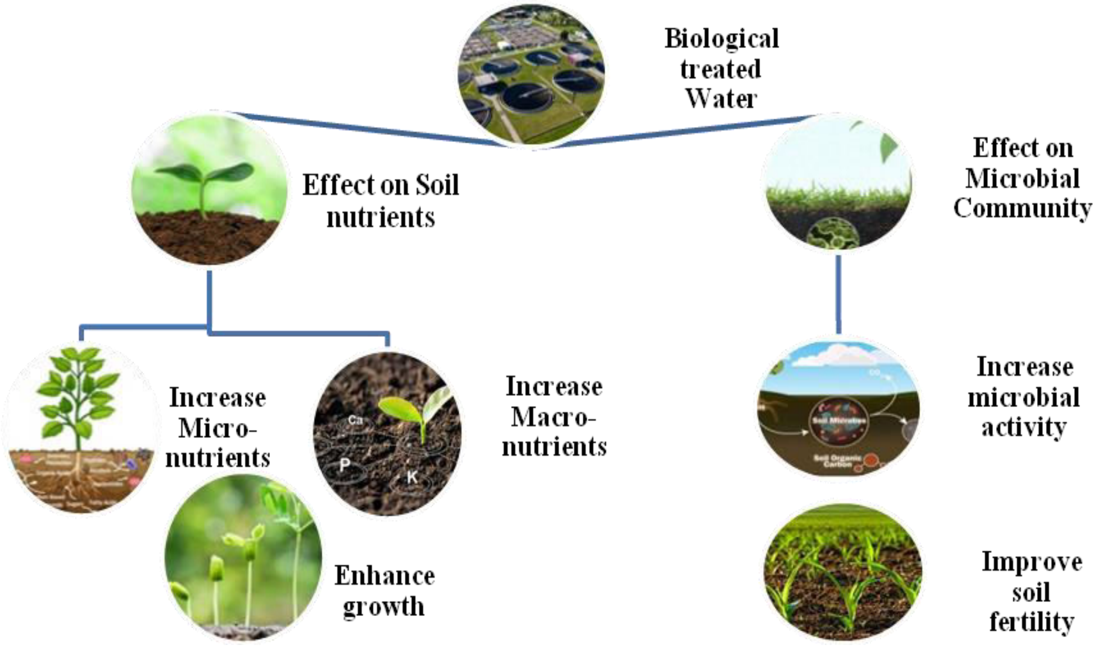


Figure.7 Waste water effect on soil, crop and soil microbial community



Organic Carbon

Soil organic carbon (SOC) plays a pivotal role in regulating nutrient retention, aggregate stability, and microbial biodiversity. Higher SOC content fosters a thriving microbial community that enhances soil structure, promotes nutrient immobilization, and facilitates organic matter mineralization (Titchou *et al.,* 2021).

Recycled wastewater contributes to SOC enrichment, thereby augmenting microbial activity and enhancing soil functions (Becerra-Castro *et al.,* 2015; Farhadkhani *et al.,* 2018). Elevated SOC levels also improve soil buffering capacity, compatibility, and nutrient recycling efficiency (Murphy, 2015).

Salinization

Salinization is a critical factor influencing irrigation water suitability. It occurs when soluble salts primarily sodium (Na), chloride (Cl), calcium (Ca), magnesium (Mg), and iron (Fe) accumulate in the soil beyond optimal thresholds (Rojas *et al.,* 2016). Soil salinity is commonly assessed using total dissolved solids (TDS) or electrical conductivity (EC) measurements. Wastewater irrigation can exacerbate salinity levels if salts are not effectively removed during treatment (Kallel *et al.,* 2012; Shakir *et al.,* 2017). High salinity adversely affects plant physiology by inducing osmotic stress, which disrupts soil-water equilibrium and impairs crop productivity (Djanaguiraman & Prasad, 2013).

Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) is a crucial indicator of soil cation balance, specifically in relation to sodium (Na), calcium (Ca), and magnesium (Mg) concentrations. Elevated SAR values detrimentally affect soil structure, permeability, and plant growth.

Additionally, SAR serves as a key determinant of irrigation water quality (Oster *et al.,* 2016). In many cases, wastewater exhibits elevated SAR values (Zema *et al.,* 2012), which, if left unchecked, can severely disrupt soil chemical, physical, and biological properties, ultimately hindering agricultural productivity (Ofori *et al.,* 2021). Consequently, lowering SAR levels in wastewater before irrigation application is imperative for sustainable soil health management.

Impact on Soil Microbial Community

Microbial communities are integral to soil ecosystems, governing critical processes such as organic matter decomposition, nutrient mineralization, enzyme activation, and soil structural stabilization (Furtak & Gajda, 2017). The biogeochemical cycling of major nutrients, including carbon, nitrogen, and phosphorus, is largely mediated by microbial activity, which facilitates the transformation of nutrients into plant-available forms (Adrover *et al.,* 2012). Additionally, soil microbes play a protective role by limiting plant uptake of harmful elements through mechanisms such as chelation and detoxification (Becerra-Castro *et al.,* 2015). The diversity and population density of soil microorganisms are key determinants of these processes. Increased microbial biodiversity enhances plant growth, sustains soil health, and mitigates pollution risks, reinforcing the ecological benefits of biologically treated wastewater irrigation.

The population and diversity of soil microbial communities can be significantly influenced by biologically treated wastewater irrigation. Several studies have reported an increase in microbial population density and species diversity in soils irrigated with biologically treated wastewater (Frenk *et al.,* 2014; Farhadkhani *et al.,* 2018). Long-term application of biologically treated wastewater has profound effects on soil microbial composition, altering community dynamics and functional potential (Hidri *et al.,* 2010). However, the impact of biologically treated wastewater on microbial communities is species-specific.

For instance, Frenk *et al.,* (2014) observed a decline in the relative abundance of Actinobacteria in soils irrigated with wastewater, while Gammaproteobacteria populations increased by approximately 10%. Additionally, an enrichment of Firmicutes, Betaproteobacteria, Acidobacteria, and Nitrospirae was reported in biologically treated wastewater-irrigated soils (Ibekwe *et al.,* 2018; Wafula *et al.,* 2015). Such microbial enrichment enhances biological soil processes, including organic matter decomposition, nutrient mineralization, and enzymatic activity (Truu *et al.,* 2009; Adrover *et al.,* 2012; Becerra-Castro *et al.,* 2015).

Soils irrigated with wastewater exhibit elevated hydrolytic enzyme activity compared to freshwater-irrigated soils, indicating enhanced organic matter degradation processes (Elifantz *et al.,* 2011). Similarly, biologically treated wastewater irrigation has been associated with significantly higher enzymatic activities, including alkaline phosphatase, urease, protease, β-glucosidase, and dehydrogenase, contributing to improved nutrient cycling and soil fertility (Del-Mar-Alguacil *et al.,* 2012).

The nutrient and organic matter content of wastewater stimulates diverse microbial metabolic pathways, further reinforcing its role in soil ecological balance (Becerra-Castro *et al.,* 2015). However, the impact of treated wastewater on microbial activity is influenced by soil properties, microbial composition in wastewater, and irrigation practices.

Challenges and Limitations

For an efficient biological wastewater treatment system, providing an optimal environment for microbial communities is essential.

However, variations in microbial needs and logistical constraints reduce the overall effectiveness of these systems. The following challenges must be addressed to optimize biological wastewater treatment.

Selection of Suitable Treatment Technology

The selection of an appropriate wastewater treatment technology depends on wastewater composition, the required quality of treated effluent, and available resources. In some cases, chemical treatments may be preferable to biological treatments, particularly when wastewater contains toxic substances or non-biodegradable organic compounds (Spichiger-Keller, 2008). Chemical treatment is often more effective under such conditions, as biological methods may fail due to microbial inhibition (Abdel-Shafy *et al.,* 2023).

Aeration Facility

Aeration is a critical design factor in biological wastewater treatment systems (Rittmann, 1987). Anaerobic or anoxic systems require conditions that facilitate the proliferation of specific microbial groups, whereas aerobic systems necessitate continuous oxygen supply for optimal microbial performance.

While aeration enhances biological activity, it also increases operational costs, particularly due to higher electricity consumption (Meylemans, 2023).

pH Maintenance

Maintaining optimal pH levels is crucial for microbial community stability and function. Wastewater composition influences pH, necessitating continuous monitoring and adjustments to maintain an optimal range (Devda *et al.,* 2021). However, the differing pH preferences of various microbial species pose a significant challenge. A well-designed pH regulation system is essential to ensure the effectiveness of biological treatment processes.

Adherence to Regulation

Effective biological wastewater treatment must meet regulatory standards by removing contaminants such as heavy metals, pathogens, and other pollutants (Blumenthal *et al.,* 2000). Compliance with water quality regulations depends on the chosen treatment technology and adherence to operational and maintenance protocols (Yusof *et al.,* 2008).

Wastewater reuse is a viable strategy to address water scarcity and food security challenges. The necessity of wastewater reuse has increased due to climate change and rising global populations. Wastewater reuse is particularly critical in regions with limited freshwater availability and high agricultural water demand. Agriculture, as the largest consumer of water resources, presents a substantial opportunity for wastewater reuse. Utilizing treated wastewater for irrigation ensures a consistent water supply while also delivering essential nutrients, thereby enhancing crop productivity. However, the direct use of untreated wastewater in agriculture, aquaculture, or human consumption poses significant environmental and health risks. Contaminants such as heavy metals, pathogenic organisms, and other pollutants present in wastewater can degrade soil quality, affect crop safety, and pose health hazards to consumers.

Various wastewater treatment methods exist to make wastewater suitable for reuse. This review examined different wastewater treatment techniques, highlighting their benefits and limitations. Chemical treatments effectively remove persistent pollutants but pose challenges related to sludge disposal. Advanced treatment technologies require substantial capital investment and ongoing maintenance. Biological treatment methods offer a sustainable alternative by reducing sludge production and energy costs.

Irrigation with biologically treated wastewater enhances plant growth, improves soil structure, and supports microbial activity. The high organic matter content in biologically treated wastewater fosters soil stability and nutrient mineralization. Furthermore, biological treatment processes can achieve high-quality treated water suitable for agricultural reuse.

However, despite its numerous advantages, biological wastewater treatment has some limitations, including the need for specific environmental conditions (e.g., oxygen levels, pH) and specialized system designs. Nevertheless, the overall sustainability and effectiveness of biological treatment make it a promising option for wastewater management.

Author Contributions

Samra Naz: Investigation, formal analysis, writing—original draft. Iftikhar Ali Ahmad: Validation, methodology, writing—reviewing. Abiha Arshad:—Formal analysis, writing—review and editing. Ammara Shoukat: Investigation, writing—reviewing. Chanda Shaheen: Resources, investigation writing—reviewing. Rimsha Aslam: Validation, formal analysis, writing—reviewing. Azqa Nawaz: Conceptualization, methodology, data curation, supervision, writing—reviewing the final version of the manuscript. Shanza Ahmed: Investigation, formal analysis, writing—original draft. Samra Saeed: Validation, methodology, writing—reviewing. Muhammad Farhan Qadir:—Formal analysis, writing—review and editing. Muhammad Mehran: Investigation, writing—reviewing. Sharjeel Haider: Resources, investigation writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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