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From Waste to Resource : Advances in Wastewater Treatment for Agricultural Reuse

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ABSTRACT

The burgeoning population of India is projected to surpass 1.5 billion by the year 2050. The growing pace of urbanization and industrialization, is expected to significantly increase water demand and wastewater generation. Currently, domestic and industrial use account for 15% of water reserves of India, by 2050 this percentage is expected to increase to 30%. Treated wastewater has gained significant importance as a resource for peri urban agriculture. However untreated wastewater poses serious environmental and health risks due to the presence of toxic metals, micro contaminants and pathogens. To address these challenges advanced wastewater treatment technologies are crucial. Conventional methods include sequential wastewater treatment stages that can remove solids, organic matter and other pollutants, improving the water quality for safe agricultural reuse. Advanced treatment technologies can target specific contaminants like xenobiotics and persistent organic pollutants. These tailored and innovative strategies are crucial for optimizing treatment efficiency. The review examines latest developments in wastewater treatment for agricultural use, highlighting their role in improving agricultural resilience and livelihoods of millions of Indian farmers.

Keywords Wastewater treatment, Conventional methods, Advanced methods, Agriculture.

INTRODUCTION

The Indian population is projected to surpass 1.5 billion by 2050, with more than 50% expected to reside in urban areas. Anthropogenic wastewater of various composition will increase due to the population boom, urbanization, industrialization and lifestyle changes. Approximately 15% of India's water resources are being used for industrial and domestic purposes. This figure is expected to rise to approximately 30% by the year 2050. By that time, the annual water demand from urban populations is expected to reach

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around 90 km^3 while the industrial sector's demand is projected to be around 81 km^3 (CPCB 2021). Historically, treated sewage water has been viewed as a valuable resource for peri urban agriculture due to its high content of biodegradable materials and essential plant nutrients (Minhas and Samra 2004). The amount of organic microcontaminants and hazardous metals present in this water is rising as the civilization and lifestyle changes. Domestic, industrial and storm water are all channelled into the same system, which complicates the treatment and reuse of wastewater. In India, the capacity of sewage treatment is only a small portion of the total sewage generated, resulting in much of the irrigation relying on untreated wastewater. The cultivation of vegetables irrigated with untreated sewage can result in significant health hazards, particularly for those that are consumed raw. Ensuring environmental sanitation and preventing disease among workers involved in farming operations are crucial hygiene concerns for urban local authorities. Wastewater use in peri urban agriculture to fulfil the feed demands of the diary sector is a potential pathway for the transfer of contaminants. Studies have shown that grasses, forages, milk and animal serum have higher concentrations of biotoxins, such as heavy metals, pesticides, and fungicides (Raschid-Sally and Jayakody 2008, Qadir *et al.* 2010, Amerasinghe *et al.* 2013). The direct release of untreated wastewater into lakes and rivers can lead to eutrophication, which can decrease the aquatic productivity. Despite these environmental concerns, it is also true that irrigation with wastewater can be a crucial opportunity to improve the livelihood of millions of peri urban farmers, enabling them to produce crops that would otherwise not be feasible if they had no access to additional water due to scarcity. Effective wastewater treatment techniques must be developed and put in practice in order to reduce the hazards associated with wastewater irrigation. Adequate treatment methods can preserve nutrients present in wastewater and can avoid harmful contaminants like heavy metals, pesticides and pathogens, rendering it a feasible choice for agricultural reuse. Wastewater compositions may differ depending on the sources and this difference highlights the need for careful consideration of treatment methods. For example, industrial effluent may contain higher concentrations of hazardous chemicals and heavy metals, requiring more stringent treatment processes, while domestic wastewater may primarily contain organic matter and nutrients. Choosing treatment technologies to the specific type of wastewater can optimize efficiency and safety. Wastewater treatment thus assumes an important role in supporting peri-urban agriculture by providing a reliable water source while safeguarding soil health and public safety. In addition, adequate wastewater treatment is vital for safeguarding aquatic ecosystems by preventing the release of untreated effluent into water bodies, which can cause a series of eutrophication and biodiversity loss. By investing in and promoting advanced treatment technologies, India can address the dual challenge of water scarcity and agricultural productivity. In the long term, establishing robust wastewater treatment systems will be essential in ensuring the increasing demand for water resources in a sustainable manner, especially as the population grows and urban areas continue to expand.

Therefore, the advancement of wastewater treatment strategies is not just an environmental necessity but also an opportunity to improve agricultural resilience, enhance food security, and enhance the living standard of millions of farmers reliant on agriculture. This review highlights recent advances in wastewater treatment for agricultural reuse, examining innovative strategies and technologies that improve the secure and sustainable use of treated wastewater in agriculture.

Wastewater treatment

Rising concerns about toxicity and the prolonged environment impacts, especially on aquatic habitats, have intensified the need to prevent the release of potentially harmful compounds, organic pollutants, and particular chemicals found in wastewater. Biological treatment methods can eliminate about 90% of added chemicals. However, there is an increasing need for the complete removal of organic pollutants, not just those that are easily biodegradable. This also includes the reduction of specific chemical compounds and the removal of both chronic and acute toxicity (Shevah 2009).

Traditional wastewater treatment utilizes a combination of physical, chemical and biological

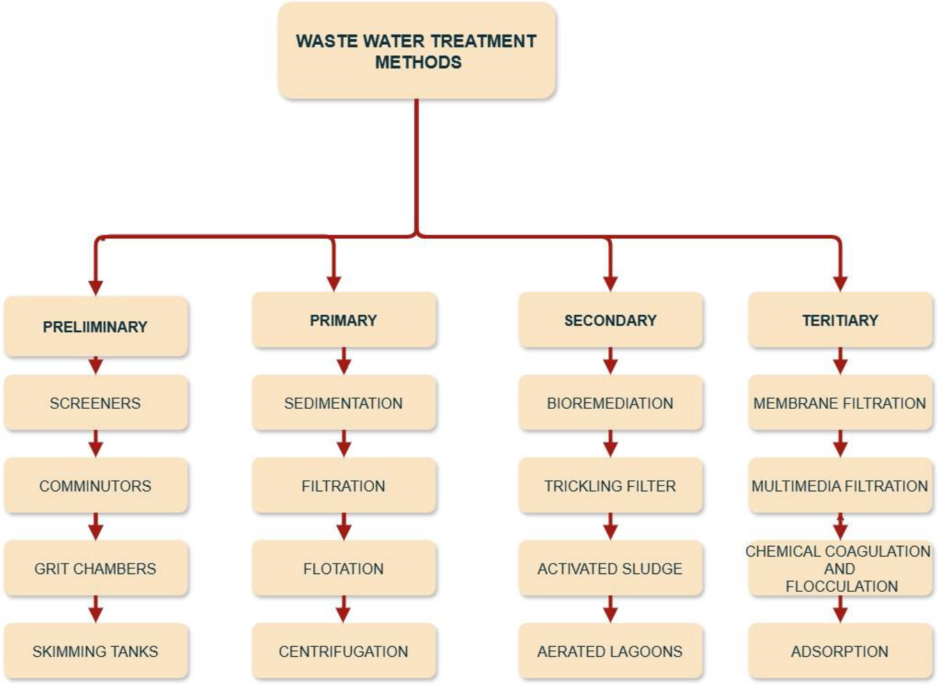

Fig. 1. Levels of waste water treatment methods for irrigation.

methods to remove solids, organic matter, and nutrients from wastewater. The process involves multiple stages: Preliminary, primary, secondary and tertiary treatment. Preliminary stage separates floating materials and removes oils and grease, reducing BOD by 15–30%. Primary treatment eliminates 5 to 50% of BOD, 50 to 70% of total suspended solids (TSS), and approximately 65% of oil and grease. Secondary treatment modifies organic matter, and tertiary treatment removes specific constituents. The final cleaning process enhances the wastewater quality before it is reused, recycled, or discharged (FAO 2004). From a public health perspective, it is crucial to treat wastewater before its use in agriculture. The levels of waste water treatment methods for irrigation can be grouped as in Fig. 1.

Preliminary treatment

Preliminary treatment is done to eliminate floating materials (such as leaves, paper and rags) and settleable inorganic solids (like sand and grit) that are commonly present in raw wastewater. This removal is essential for improving the operation and maintenance of the following treatment stages. Skimming tanks, grit chambers, comminutors and screeners are the four main equipments used in preliminary screening process.

Screeners

A screener is a device that removes suspended particles and floating objects from wastewater by means of apertures that are usually consistent in size. Screening is performed by directing sewage through various screens that have different pore sizes. Depending on the size of their openings, screeners are classified as coarse, medium and fine. Coarse screens have larger openings ranging from 75–150 mm, while medium screens have openings between 20–50 mm, and fine screens have openings smaller than 20 mm. Commonly used screen types include fixed bar screens, disc type fine screens and drum type fine screens. The water particles and many other contaminants are small enough to pass through these screens, but many of the suspended solids are not. These solids are trapped in the screens, where they can be removed manually or automatically (Manasa and Mehta 2020).

Comminutors

Comminutors are devices that can filter and shred materials into sizes ranging from 6 to 20 mm, while retaining the shredded solids in the flow stream. It slices and diminishes large pieces of organic material into smaller fragments, helping to prevent solids from causing blockages in the flow. Comminutors are typically positioned before the grit chamber. They are made up of a screen, a rotating cutter, and a stationary cutter. The solids can pass through the screen and are cut or shredded by the rotating and stationary cutters (Sidwick 2007).

Grit chambers

Grit removal is the next phase of preliminary wastewater treatment. Inorganic particles with a specific gravity of 2.65 can be eliminated with the help of grit removal basins. Grit chambers can effectively remove particles like sand, gravel, grit, egg shells, glass shards, metal fragments, and other non-putrescible materials that could clog channels or harm pumps. This method relies on the process of sedimentation driven by gravitational forces (Sidwick 2007).

Skimming tanks

Skimming tanks are employed to remove grease and fatty oils from the sewage. If oil and grease are not eliminated from the sewage water, they will form scum on the surface, leading to unpleasant odors. This scum hinders reoxygenation and results in anaerobic conditions. Long rectangular tanks with at least two connected longitudinal baffle walls are known as skimming tanks. At the bottom of the tank are air diffusors. Oily and greasy materials in the sewage congeal and solidify when compressed air is added from tank's floor because of the ascending air bubbles. After that, this material is sent to a side compartment called the stilling compartment, where it can be extracted mechanically or manually (Sidwick 2007) wastewater after preliminary treatment cannot be used for irrigation and should be further subjected to other treatment methods (Minhas *et al.* 2022).

Primary treatment

Primary treatment focuses on eliminating fine suspended organic solids that are not removed during the preliminary treatment phase. It is a process that removes settleable organic and inorganic solids through various processes like sedimentation, filtration, flotation and centrifugation. Additionally, it can effectively remove heavy metals, phosphorus and organic nitrogen that are attached to the solids. Water after primary treatment can be used for irrigating non food crops adopting flood irrigation (Minhas *et al.* 2022). Various primary treatment methods include:

Sedimentation

Sedimentation is a physical water treatment technique that utilizes gravity to separate suspended solids. Its effectiveness is influenced by the size, zeta potential, and specific gravity of the solids. It eliminates contaminants such as suspended particles, heavy metal ions, microorganisms and effluents from wastewater, however it is not effective in removing dissolved particles (Bairagi and Ali 2020).

Filtration

Filtration is a crucial process in water treatment, primarily involving the removal of suspended solids through a bed filled with granular media. Coagulation with a suitable coagulant can increase the range of detained particles. It focuses on turbidity, color, microorganisms and particulates, which are already present or formed through pretreatment (Cescon and Jiang 2020). Different types of filters used in wastewater treatment are slow sand filters with biofilms for contaminant removal, screen filters for high flow particulate removal, and disc filters designed to capture sand and other particulates (Marsh 2023). Types of filters and their key characteristics are depicted in the Fig. 2.

Flotation

Flotation process is a separation technique that employs gas bubbles as a transport medium, enabling suspended particulate matter to adhere to the bubbles and rise to the water surface, defying the force

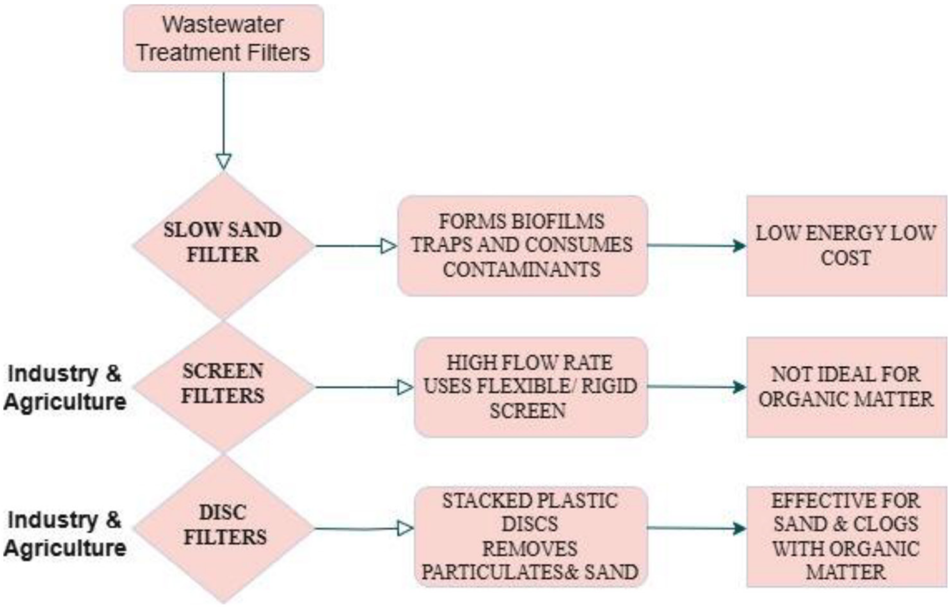

Fig. 2. Types of filters and their key characteristics.

of gravity. This process is particularly effective in treating reservoir water with algae, natural color or organic matter and is more efficient than sedimentation (Kyzas and Matis 2018).

Centrifugation

Centrifugation is a widely used method for sludge dewatering. The primary benefit of this technology is that solid liquid separation occurs in complete isolation from the outside. The machine is compact, versatile, and easy to operate. Its mechanism for separating solids or liquids resembles that of sedimentation, but the solids experience forces that are significantly greater than that of gravity (Canziani and Spinosa 2019).

Secondary treatment

Secondary treatment is a process that follows primary treatment to remove residual organic matter and suspended particulates from the effluent. The removal of biodegradable dissolved and colloidal organic materials is accomplished through aerobic biological processes. These processes may vary in their oxygen supply and the speed at which organisms break down organic matter (FAO 2004).

Bioremediation

Bioremediation is a technique that utilizes naturally occurring microorganisms to convert environmental waste into less harmful or non harmful forms (Raychoudhury and Prajapati 2020). This environment friendly and commercially viable approach break down or detoxifies the pollutants in water using bacteria, fungi or plants (Wang and Tam 2021). The formation of microbial consortia or microflora that are indigenous to contaminated locations and capable of carrying out essential tasks is important for the success of bioremediation.

A study conducted by Aslam *et al.* (2023) revealed that rice cultivars irrigated with treated domestic wastewater (DWW) showed higher growth parameters compared to those grown in untreated DWW. The study demonstrated a bioremediation efficiency of 90%, with the total soluble solids (TSS) value reducing from 930 mg L^{-1} to 300 mg L^{-1} after biotreatment, and BOD and COD levels significantly decreased from 295.7 mg L^{-1} and 412.8 mg L^{-1} to 171.5 mg L^{-1} and 140 mg L^{-1}, respectively. Electrical conductivity, total dissolved salts, salinity, pH and iron content, were among the physico-chemical parameters that decreased after the biotreatment with *Alcaligenes faecalis* MT477813.

Trickling filter

Trickling filter is a technique that involves microorganisms being attached to an inert medium, such as a round tank, through which wastewater trickles over a filter media. The media functions as an adsorbent, allowing microorganisms like bacteria, algae, fungi and protozoa to absorb matter. Although this technique efficiently eliminates suspended particles and biological oxygen demand, it needs significant maintenance and operating expenses (Xu *et al.* 2015).

A study by Aslam *et al.* (2017) reported that a trickling filter system can achieve BOD and COD with removal efficiencies of 69–78% and 65–80% respectively. Additionally, the system reduced solids, turbidity (32–54%) and color (25–42%), making treated effluents suitable for reuse as irrigation water supplement in underdeveloped or developing countries.

Activated sludge

Activated sludge is a treatment method that uses a variety of microorganisms, including bacteria, fungi and protozoa to remove organic matter from wastewater. This method incorporates aeration and settling tanks, along with equipment such as waste pumps, mixers, blowers and flow measurement devices. The process requires vigorus aeration to promote the formation of microbial flocs that effectively degrade organic matter, which are then removed through sedimentation. To maintain the activity of the bacteria in the tank, a portion of the activated sludge is reused (Liu *et al.* 2011). This method occupies a small space and produces better waste quality. The only disadvantage is the higher concentration of BOD at one end of the tank (Xu *et al.* 2015).

A study was carried out to examine the effect of sewage sludge on the yield and yield attributes of marigold. The results revealed that treatment receiving potting mixture and sewage sludge in the 9:1 ratio recorded the maximum number of flowers (79.60 per plant) and flower yield of 706.36 g per plant. However, the decrease observed in the treatments receiving more than 2 parts of sewage sludge may be due to the negative influence of heavy metals present in sludge (Anjana 2017).

Aerated lagoons

Aerated lagoons are aerobic suspended growth systems employed for industrial and municipal wastewater treatment, known for their high tolerance to sudden load variations and construction. They are preferred over other methods like activated sludge and are regarded as a viable alternative in both developed and developing nations. These deep waste stabilization ponds use mechanical aerators to stabilize organic matter in sewage and can function as a treatment system that lies between oxidation ponds and activated sludge systems (Kuzniewski 2023).

Tertiary treatment

Tertiary treatment denotes an extra stage of treatment for biologically processed effluent, tailored to its intended applications. Micropollutants, suspended particles, residual dissolved inorganic solids, heavy metals, non-biodegradable substances, pathogenic microorganisms and nutrients which are not addressed during secondary treatment can be removed in this phase. This stage can be designed to eliminate nutrients (if not removed in the secondary treatment step) pathogenic organisms, non-biodegradable compounds, heavy metals, residual inorganic dissolved solids, suspended solids and micropollutants. The final effluent meets more stringent standards than those attained through secondary treatment alone, enabling its reuse in specific scenarios (Keisham *et al*. 2021). Several tertiary treatment processes that can be employed depending on the purpose are briefly discussed below:

Membrane filtration

Membrane filtration has garnered significant attention in recent years due to its ability to remove pollutants from various sources. The use of membrane technology into an existing industrial process can lower the cost and decrease the overall energy consumption

Table 1. Types and membrane and filtrations.

Membrane filtration type	Pore size	Applications	Materials	Key characteristics	References
Microfiltration (MF)	10-0.1 µm	Reduction of organic carbon and COD	Ceramic, Polymeric	Oldest technology, low cost, used for large particles	Behroozi and Ataabadi (2021)
Ultrafiltration (UF)	0.1-0.01 µm	Dairy, urban waste water treatment	Polymeric	Retains suspended solids, colloids, emulsions, bacteria and viruses	Rani *et al.* (2021)
Nanofiltration (NF)	0.010-0.001 µm	Industrial and commercial	Polymeric (polyamide)	High retention capacity, low pressure, selective separation	Fatima *et al.* (2019)

(Deemter *et al.* 2022). Existing membrane processes include microfiltration, ultrafiltration and nanofiltration (Table 1).

Multimedia filtration

Filtration is a simple and cost effective treatment method for eliminating pollutants from wastewater using a porous. Three or more different kinds of packing materials can be used in multimedia filters. They consist of various packing materials in different sizes, stacked to a depth of 0.75 m to 1 m. The attached growth process serves as the foundation for the filtration process. The microorganisms that break down organic material or nutrients are affixed to a packing material. Redwood, rock, gravel, slag, sand and other synthetic materials are the biofilm packing materials used in attached growth processes (Gulhane and Charpe 2015).

Chemical coagulation and flocculation

Coagulation-flocculation is a process employed to treat wastewater effluents by enhancing water quality indicators to comply with irrigation standards (Teh *et al.* 2016). It uses chemicals and flocculants to neutralize the charge on particles, causing colloidal particles to agglomerate, which can then be removed through sedimentation or filtration (Vigneswaran *et al.* 2005). Pre treatment with poly aluminium chloride and a polymer can enhance the coagulation process (Teh *et al.* 2016). The introduction of a coagulant destabilizes colloidal particles, resulting in the formation of solid lumps that settle and are removed through gravity sedimentation or filtration. This process diminishes surface charges and creates complex hydrous oxides that entrap unwanted pollutants. It involves choosing appropriate chemicals and concentrations, mixing wastewater samples with coagulant and flocculent, and analyzing the supernatant. Coagulation characteristics can vary based on the type of pollutant present (Wang *et al.* 2017).

Adsorption

The physico-chemical characteristics of the adsorbent and heavy metals, as well as operational parameters including temperature, adsorbent quantity, pH, adsorption time, and initial metal ion concentration are all crucial to the adsorption mechanism in wastewater treatment. Adsorption of heavy metal ions onto adsorbent surfaces is cost effective, efficient and easy to implement (Qasem *et al.* 2021). Activated carbon, a commonly used sorbent can effectively remove organic contaminants from wastewater because of its high surface area and large volume of micropores and mesopores (Owlad *et al.* 2009). Yakubu *et al.* (2021) revealed that the use of 100 g activated carbon completely decontaminated Ni from municipal wastewater for vegetable irrigation.

Advanced waste water treatment methods

Conventional methods for treating wastewater involve a range of specific physical, chemical, and biological methods. The main goal of these methods is to eliminate solids, organic materials, and nutrients from wastewater. They offer several benefits, includ-

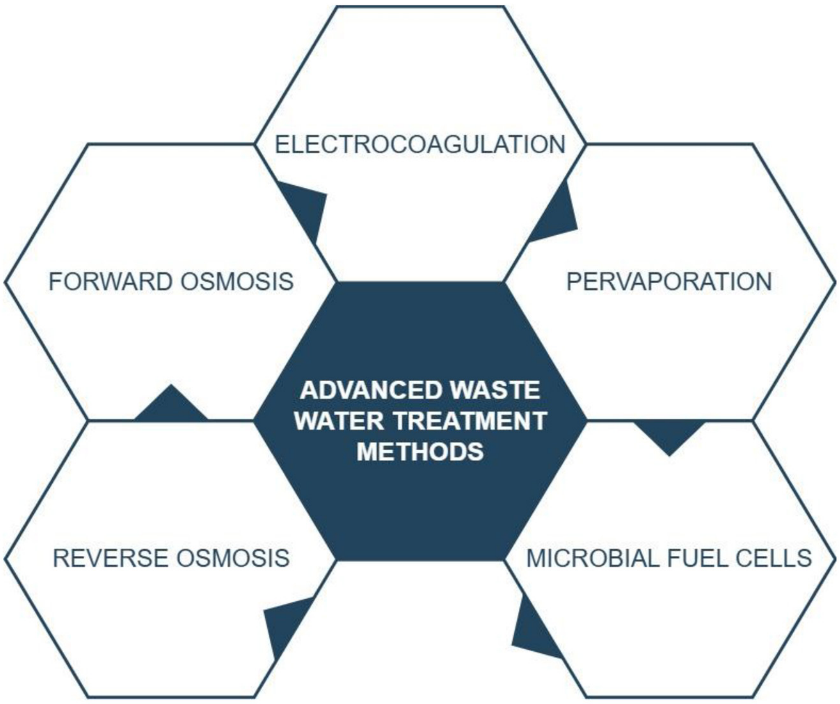

Fig. 3. Advanced wastewater treatment methods.

ing compact design, efficiency, ease of installation and affordability. In addition to these advantageous features, it also presents several limitations. It is energy intensive, requires yearly maintenance, involves chemical consumption, is inefficient in eliminating metal ions at low concentrations, and results in larger sludge production, handling and disposal problems. These issues have prompted researchers to explore and adopt more dependable advanced technologies. Some examples are reverse osmosis, forward osmosis, electrocoagulation, pervaporation and microbial fuel cells Fig. 3.

Reverse osmosis

Reverse osmosis (RO) can retain everything except water molecules. The transmembrane pressure during RO operation ranges between 15 to 27 bar for brackish water, and 50–80 bar for seawater dezalination. The pore size of the membrane ranges between 0.001-0.0001 µm. Reverse osmosis functions at extremely high pressures, which results in significant energy consumption. Fouling is a major problem of RO membrane, making prefiltration of the matrix essential. Reverse osmosis is also used as an alternative water source for irrigation activities but requires remineralization before use (Rabiee *et al.* 2019).

In a study by Mzahma *et al.* (2023) to assess the suitability of different qualities of water for irrigating *Sesbania bispinosa* plants. The treated water from three membrane processes viz. UF, NF and RO was compared with that from biological treatment. SO_4^{2-}, Na^+, and Cl^- ions were removed by NF at rates of 83%, 61% and 55%, respectively. In contrast, RO membranes, achieved approximately 96% reduction of these ions. These findings indicate that utilizing NF and RO water for irrigation could be a more effective and environmentally friendly alternative compared to BT and UF water.

Forward osmosis

Forward osmosis is a commercial technique utilized for water dezalination, utilizing a salt concentration gradient as the driving force across a membrane. Water from the feed solution on one side of the membrane, moves to a draw solution with a higher osmotic pressure on the other side of the membrane. There is no need of an external pressure throughout the process. The resulting diluted draw solution is subsequently processed to separate it from the product water (Heo *et al.* 2020).

Wahid *et al.* (2021) highlighted that the fertilizer drawn forward osmosis has the potential for recover and recycle both water and nutrients from agricultural wastewater, particularly from palm oil mill effluent, which is composed of 95% water and is high in nutrients.

Electrocoagulation

Electrocoagulation is a water treatment technology that uses an electric charge to aggregate suspended particles in water. This method effectively removes a variety of contaminants, including suspended solids, heavy metals, emulsified oils, and bacteria (Ammar *et al.* 2023). The process involves passing an electric current between two electrodes, which leads to the electrolytic oxidation of the anode material and produces a coagulant (Saleem *et al.* 2011). Within the electrochemical cell, disinfection agents are generated, and when the total dissolved solids in wastewater is high, additional electrolytes are unnecessary as the generated solids can enhance current flow through the wastewater. Both iron and aluminium electrodes can be utilized, with iron electrode being more effective for achieving better water quality (Zaied *et al.* 2020).

A study conducted by Saleem *et al.* (2011) demonstrated that utilizing a current density of 24.7 mA cm^{-2} with a 5 cm inter electrode spacing enabled the removal of 91.8% turbidity, 72.2% COD, and 68.5% TSS within 30 minutes of electrochemical treatment. The quality of the treated wastewater was assessed against the international standards for reuse, confirming that it met safety criteria for landscape irrigation and plantation, with all parameters falling within the acceptable limits.

Pervaporation

Pervaporation is a membrane based separation technique that uses non porous membranes made of polymeric or ceramic materials to separate both binary and multi component mixtures (Eljaddi *et al.* 2021). It plays a vital role in wastewater treatment by separating components that have similar molecular sizes. It is an energy saving and environment friendly technology, making it a valuable alternative to traditional separation processes (Obotey- Ezugbe and Rathilal 2020). Pervaporation has promising applications such as treating brackish ground water and recycling wastewater for agricultural micro irrigation (Quinones-Bolanos *et al*. 2005).

Microbial fuel cell technology

Microbial fuel cell technology is an effective method for treating wastewater to ensure it meets the requirements for irrigation (Munoz-Cupa *et al.* 2021). Biochemical devices known as microbial fuel cells can convert chemical energy of organic matter into electrical energy. The cell consists of a proton exchange membrane, a cathode chamber, and an anaerobic anode chamber. Bacteria obtain energy by transferring electrons from their metabolic processes to the anode, which serves as an electron acceptor. These electrons combine with oxygen and hydrogen ion to generate water. Microbial fuel cells can be used with mixed and pure bacteria cultures, and have been successfully used to treat and generate electricity from various types of wastewaters.

The heavily contaminated palm oil mill effluent (POME), known for its elevated levels of BOD and COD serves as an ideal substrate for microbial fuel cells (MFCs). Using a double chamber MFC with POME as the substrate can achieve a maximum power generation of 45 mW m^{-2}, along with a 45 % reduction in COD over a period of 15 days (Baranitharan *et al.* 2013). Abourached *et al.* (2016) reported MFC as a viable option to reclaim wastewater to meet irrigation requirement in semi arid regions of California.

Regulations and standards on wastewater reuse in agriculture

Advancements in treatment technologies have resulted in the establishment of guidelines for the safe reuse

Table 2. WHO guidelines on safe use of wastewater. Note: PPY- person per year, DALY- disability adjusted life year. (Source: WHO 2006, Shoushtarian and Negahban-Azar 2020).

Year	Title	Main goals	Key features	Limitation
1973	Reuse of effluents: Methods of wastewater treatment and health safeguards	Protect public health	Guide safe application of wastewater and excrete in agriculture and aquaculture	Minimal health risk approach, lacked epidemiological studies
1989	Health guidelines for the use of wastewater in agriculture and aquaculture	Focus on microbiological quality of recycled water for irrigation, include risk assessment	Necessary information to determine societies tolerable risks	Lacked information on surveillance guidelines
2006	Safe use of wastewater excreta and greywater	Form governmental guidelines, and regulations for wastewater management based on situations	Significant improvement in risk assessment, microbiological analysis, health risk management, PPY DALY estimates	-------------

of treated water (TW) in irrigation and other fields. Most of the studies are primarily focused on human health, lacking in information on potential hazardous pollutants and significant inconsistencies in data.

Guidelines for the safe use of wastewater for irrigation were released by the World Health Organization (WHO) in 1970, 1989 and 2006 (Table 2). These guidelines are designed to address public health hazards and reinforce government regulations regarding wastewater management. The first publication, “Reuse of effluents: Methods of wastewater treatment and health safeguards,” released in 1973, was a crucial source of information for worldwide standards in wastewater management. Its main objectives were to safeguard public health and provide guidance for the appropriate use of wastewater and excreta in agriculture and aquaculture. However, it lacked epidemiological studies and had minimal health risk approach.

In 1989, WHO updated this guideline with a document titled “Health guidelines for the use of wastewater in agriculture and aquaculture,” which incorporated a complete epidemiological studies analysis. In addition to risk assessments and the data required to ascertain the acceptable risk to society, this version focused on the microbiological quality of recycled water used for irrigation and included risk assessments, as well as the necessary information to determine the tolerable risk of society. Despite these additions, it did not provide any information on surveillance guidelines (Mara *et al*. 2007). “Safe use of wastewater, excreta and greywater’’ was the title of the final guideline, released in 2006. This guideline was designed to assist the, Governments to create standards, rules and laws pertaining to wastewater management, that are customized to the unique circumstances of various countries (Jaramillo and Restrepo 2017). The guidelines established by the WHO, US Environmental Protection Agency, and FAO form the foundation for developing regulations in various countries. In the absence of national guidelines, these recommendations are proposed as a viable solution. Water quality standards for crop production, soil fertility, crop productivity, and environmental protection are the main focus of FAO guideline (Alobaidy *et al.* 2010). The quality of irrigation water is assessed using a range of parameters, including pH, electrical conductivity, BOD, COD, TSS sodium adsorption ratio (SAR), soluble sodium percentage (SSP), exchangeable sodium percentage (ESP), residual sodium carbonate (RSC), and toxic elements (Pedrero *et al.* 2010).

Consequently, continuous monitoring of these parameters is advised, as they can affect soil, crops and the surrounding environment.

In India, the treated effluent must comply with the standards set for irrigation as outlined in the Environmental Protection Rules of 1986/consent. The effluent should also adhere to a Total Dissolved Solid (TDS) limit to 2100 mg L^{-1} and SAR ideally below

18 W kg^{-1} but not exceeding than 26 W kg^{-1} depending on the type of soil or crop. Additionally, it must meet any other criteria recommended by agricultural universities or institutes (CPCB 2019).

Innovations in wastewater treatment and reuse

Internet of things (IoT) based applications

Conventional methods for monitoring water quality in wastewater treatment face limitations due to their labor intensive processes, high operational costs, and inability to provide real time data. A reliable water quality management system is needed to assess performance and maintain a decision making database. The implementation of IoT can enhance crisis response time, standardize management practices, conserve energy, and can also boost the economic efficiency by continuously monitoring the processes and equipment in wastewater treatment facilities (Su *et al.* 2020).

"Augeias'' is a pioneering initiative aimed at enhancing the reuse of treated waste water in precision agriculture through an intelligent internet of things (IoT) management platform. The project aimed to create a smart ecosystem that guarantees the safe and efficient reuse of wastewater from treatment plants for irrigation. The project integrated advanced IoT systems with low power wide area networks, cloud computing, data analytics, and artificial intelligence technologies to optimize decision making processes for farmers and utility companies (Louta *et al.* 2021).

A study conducted by Jimenez *et al.* (2021) introduced a comprehensive system that integrates a smart wireless sensor network designed to detect pollutants such as high salinity and oil spills. When the contamination is identified the system redirected the affected water into auxiliary canals where biosorption treatment using biomass materials occurs before the water is returned to the main irrigation canal. The architecture of the system includes multiple sensor nodes that are outfitted with inexpensive sensors to monitor the real time water quality. A communication protocol facilitates efficient data transmission, while artificial intelligence algorithms analyze the data to determine suitable treatment measures. This innovative approach aims to improve water quality management in agriculture, ultimately minimizing health risk associated with contaminated irrigation water.

GIS-based approach

In developing countries like India domestic wastewater management is challenging due to the lack of quality observation data. Remote sensing (RS) and GIS based approaches help to bridge this data gap by offering prompt information at low cost. These methods can be widely used in wastewater management for site selection, pollution hotspot identification, and treated wastewater irrigation (Singh 2019). Data needed includes topography, land use, geology, distance from major waterbodies, climatic data, and effluent wastewater characteristics. Integration of these methodologies at the study area level enables an easy assessment of the suitability of natural treatment systems (Li *et al.* 2017).

The way forward

Tailored technological solutions are required to address the gap between wastewater generation and treatment. These may include centralized or decentralized infrastructure, conventional or advanced solutions, and nature based approaches. A holistic approach should be considered ensuring a "no-one-size-fits-all" solution. The advancement of affordable data monitoring tools can facilitate effective monitoring and can also raise awareness among stakeholders regarding load generation and reuse. Techniques utilizing IoTs, WSNs, remote sensing and GIS can deliver real time data and enhanced spatiotemporal resolutions. These devices should be employed for monitoring, reusing, and recycling wastewater for agricultural purposes.

CONCLUSION

Wastewater irrigation is a significant solution to the global water deficit, aiding in agricultural irrigation. The use of suitable technologies can minimize risks and provide substantial benefits. Irrigation with treated wastewater is expected to grow, especially in arid and semi arid areas. Essential technical elements and policies in wastewater irrigation encompass improved management of untreated wastewater on farms and within farming communities, guidelines for selecting appropriate crops and cultural practices, and approaches to protect farm workers and consumers from hazardous pathogens and chemicals. Additional considerations include the technical expertise required for operation and maintenance, costs, power demands, and other relevant factors. Public perception is a challenge, but as freshwater sources decrease, the public may accept treating wastewater. Therefore, it is crucial to draw lessons from unplanned and planned agricultural reuse scenarios throughout the world and develop more effective policies to fully realize the potential of wastewater irrigation.

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