

Review Paper

A Review of Treatment Wetland Typologies for Wastewater Treatment in Mitigating Freshwater Scarcity

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ABSTRACT

The demand for freshwater continues to increase due to expanding agricultural activities, population growth, industrialization, and climate change-induced droughts. These challenges are further exacerbated by the indiscriminate discharge of untreated wastewater into surface water bodies, leading to the degradation of freshwater resources. Wastewater reuse for irrigation and environmental applications represents a sustainable approach to alleviating freshwater scarcity. However, its implementation is constrained by technical, regulatory, and safety considerations. This review synthesizes current research on wastewater treatment strategies, with a particular focus on treatment wetland systems integrated with complementary technologies such as biofilters, bioreactors, filtration processes, and trophic ponds. The performance of these combined systems in improving effluent quality and enabling safe reuse is critically evaluated. The findings indicate that hybrid treatment approaches can substantially enhance contaminant removal efficiency and improve water quality for reuse. Among the examined methods, the combination of ultraviolet (UV) irradiation with the highlighted disinfection techniques is identified as a promising step for achieving high levels of wastewater decontamination.

Key words:

reuse, greywater, treatment lines, municipal wastewater, Sub-Saharan Africa

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INTRODUCTION

Freshwater use can be broadly classified into two categories: in-stream (*in situ* or non-consumptive) and withdrawal (*ex situ* or consumptive) uses. According to FAO and UN-Water (FAO and UN Water, 2024), water stress is commonly defined when renewable freshwater availability falls below approximately 1,700 m³ per capita per year. In Sub-Saharan Africa, more than one-third of the population already lives in environments where per-capita renewable resources are below this threshold, with many countries experiencing levels below 1,000 m³/person/year, i.e. the zone of chronic scarcity. Furthermore, the region has been identified as the world's most water-insecure, with all the countries rated as water-insecure and a number flagged as critically insecure. Access-based indicators reveal that only around 39% of the general population and as little as 19% in rural areas have piped water in their homes (FAO, 2015). These figures underline the urgent need for sustainable wastewater treatment and reuse solutions, including treatment wetlands, to bolster water security across the region.

Freshwater is a scarce resource globally, especially in Sub-Saharan Africa, due to long dry spells experienced in these regions (Onu et al., 2023). Sub-Saharan Africa is known for its sparse rainfall and frequent droughts. Most of

its rainfall comes from convectional cycles, but the overexploitation of surface water resources for agricultural, domestic, and industrial uses has contributed to the depletion of rivers, lakes, and reservoirs (Zamora et al., 2019). There is crippling water stress experienced in Sub-Saharan Africa compared with other thriving developing countries (Marti et al., 2011). Water is a crucial resource or raw material for irrigation, fertilizers, and pesticide application. It can also serve as a transport medium for harvested produce, and for washing and/or cooling vegetables at the post-harvest stage (Van den Akker et al., 2014).

Urbanization, industrialization, overpopulation and improper waste disposal are the major causes of freshwater contamination (Pauwels et al., 2006). Freshwater contamination is characterized by the presence of diverse pollutants, including micropollutants, heavy metals, volatile organic compounds, pathogens, and contaminants of emerging concern (CEC). According to Zamora et al. (2019), over 90% of all surface waters are contaminated with microbial pathogens such as fecal coliforms, total coliforms (Udoma et al., 2024), and *E. coli* because of the detrimental activities and lack of enlightenment of rural dwellers. Globally, a substantial proportion of wastewater—often estimated at over 80%—is discharged into the environment and freshwater without adequate treatment, posing significant risks to human health and ecosystems (Pauwels et al., 2006). Any physical contact with contaminated water bodies or consumption of vegetables irrigated with wastewater sources can lead to disease outbreaks (Amoah et al., 2011).

Wastewater is categorized in diverse ways, ranging from greywater (wastewater from bathrooms and kitchen drains), fecal sludge (wastewater from WCs, latrines, and cesspits), to industrial/municipal effluent (wastewater from residential watersheds, factories/industries and car wash outlets) (Edokpayi et al., 2017). Considering that there are substantial amounts of feces deposited in most greywater and municipal wastewater, it simply means that all wastewaters should be avoided totally or thoroughly decontaminated before the use for irrigation. Sub-Saharan Africa suffers from inadequate water supply and has several farmlands where the only source of irrigation water is the municipal effluent that is deposited into surface waters. This review aims to present low-cost alternatives for wastewater treatment systems, an updated typology of treatment wetlands (TWs), and their performance and applicability in Sub-Saharan Africa.

Wastewater Categories and Treatments:

There are about five (5) wastewater categories classified based on their sources, contaminants, and reusability. Treating such wastewater types depends on the purpose of reuse after pollutant removal. Here are the major categories and applicable treatment options that can be applied:

1. Domestic Wastewater

Domestic wastewater refers to water discharged from households and small communities (Yakubu et al., 2021), including effluents from kitchens, bathrooms, and toilets. It contains organic matter, suspended solids, nutrients, and pathogens. TWs serve as affordable and eco-friendly systems for removing organic and microbial pollutants from household discharges before reuse or safe environmental release (Osei et al., 2017).

2. Industrial Wastewater

Industrial wastewater originates from manufacturing and processing activities such as textile production, food processing, petrochemical processing, and mining. It is often rich in heavy metals, toxic chemicals, and high-strength organic compounds.

3. Stormwater Runoff

Stormwater runoff results from precipitation that flows over impervious surfaces such as roads and roofs, collecting debris, oil residues, and sediments. It contributes to surface water pollution if left untreated.

4. Greywater (Bathroom, Laundry, Kitchen)

Greywater constitutes household wastewater that excludes toilet effluents, typically coming from showers, washing machines, and sinks. Although it has lower pathogen levels than blackwater, it contains detergents, oils, and organic matter.

5. Blackwater (Urine, Feces)

Blackwater is the fraction of domestic wastewater originating from toilets and containing human excreta and urine. It is the primary source of pathogens and nutrient overload in wastewater streams (Osei et al., 2022). The provision of affordable, safe, sustainable, and reliable wastewater treatment facilities poses a major challenge in developing countries, especially those in Sub-Saharan Africa, as well as in arid and semi-arid regions of the world (Yeleliere et al., 2018).

Wastewater Treatment Lines

Treatment lines refer to the sequential and function-specific pathways through which different wastewater streams (such as greywater, urine, and feces) are collected, processed, and treated using appropriate technologies. Each

treatment line is designed to address the distinct physical, chemical, and biological characteristics of a particular wastewater fraction, thereby improving overall treatment efficiency, operational reliability, and resource recovery. The primary purpose of separating wastewater into treatment lines is to optimize pollutant removal, reduce system overload, and enable targeted treatment processes such as nutrient recovery, pathogen reduction, and organic matter degradation. By treating wastewater streams individually rather than as a mixed flow, treatment systems become more flexible, cost-effective, and environmentally sustainable.

Link between Treatment Lines and Treatment Wetlands

TWs serve as core treatment units within many wastewater treatment lines, particularly for greywater and partially treated effluents. In this context, TWs act as natural bioreactors where physical filtration, microbial degradation, and plant-mediated uptake occur simultaneously. They often function as secondary or tertiary treatment stages, polishing effluents after preliminary processes such as sedimentation, storage, or nutrient precipitation (Reddy et al., 2022). The integration of treatment lines with TWs allows wastewater to be preconditioned before entering the wetland, thus enhancing wetland performance, preventing clogging, and extending system lifespan. This linkage underscores the role of TWs not as isolated systems but as integral components of decentralized, multi-line wastewater treatment frameworks, supporting safe water reuse and resource recovery.

1. Greywater Treatment Line (Central Shaft → TWs → Evaporation Pond)

Greywater from household activities such as bathing, laundry, and cooking is first directed into a central shaft, where large solids and floating materials settle or are screened out. This primary step reduces suspended solids and prevents clogging in subsequent units. The partially clarified effluent then flows into TWs, engineered vegetated systems that promote biological degradation, nutrient uptake, and filtration through plant roots and substrate layers. Finally, the treated effluent enters an evaporation pond, where residual water is naturally lost through evaporation and solar exposure, leaving behind minimal sludge (Tortajada, 2020). This line ensures safe greywater polishing and allows for possible reuse in irrigation or landscape applications in arid and semi-arid regions.

2. Urine Treatment Line (Storage Tank → Struvite Reactor → Special Soil Filter) Urine, being nutrient-rich but pathogen-poor, is first collected separately and stored in a storage tank for a defined retention period (typically 1–3 months) to allow pathogen die-off and chemical stabilization. The stabilized urine is then fed into a struvite reactor, where magnesium salts are added to precipitate struvite (magnesium ammonium phosphate, $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$). This process captures nitrogen and phosphorus, producing a valuable fertilizer by-product. The remaining liquid fraction passes through a special soil filter, which removes residual nutrients and organic traces through adsorption and microbial activity. This treatment line exemplifies resource recovery, transforming human waste into agricultural input that aligns with circular economy principles promoted in the paper.

3. Feces Treatment Line (Composting using Struvite and Compost Combination)

Fecal matter, containing high concentrations of pathogens and organic solids, undergoes composting, a thermophilic biological process that transforms waste into stable, pathogen-free humus. In this treatment line, struvite and organic compost are combined to optimize the nutrient balance and accelerate decomposition. Struvite contributes essential minerals (especially phosphorus), while compost enhances the microbial activity and moisture balance (Onu et al., 2023). The end product is a nutrient-rich soil conditioner or biofertilizer, safe for agricultural use. This method not only sanitizes human excreta (Osei et al., 2019) but also closes the nutrient loop, reflecting the aim of the paper to present sustainable, nature-based sanitation systems that complement TWs in wastewater management.

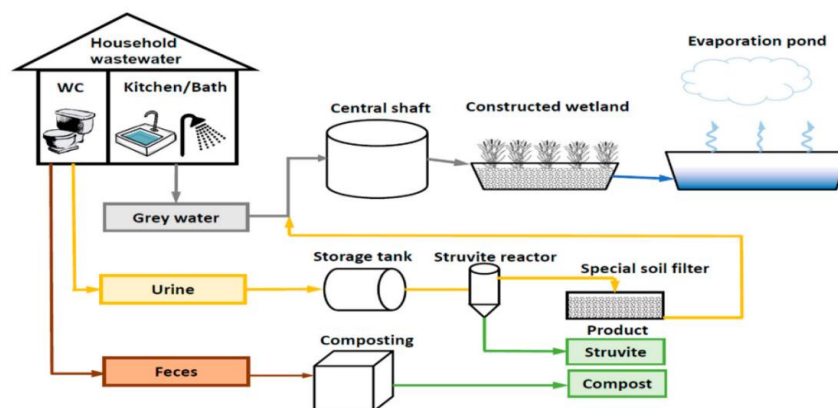


Figure 1. Sustainable treatment interventions (Source: Xiao et al., 2021)

Opting for affordable decentralized systems (Figure 1) will phase out the challenge of installing expensive centralized treatment systems (Onu et al., 2023). A great number of researchers have evaluated these facilities and proffered several solutions to mitigate the issue of inadequate treatment of contaminated irrigation sources (Xiao et al., 2021). Tortajada (2020) established the fact that Vertical Flow TWs are more efficient than their Horizontal Flow counterparts by 7.14% based on their individual pollutant removal efficiencies.

Brief History and Evolution of Typologies of Treatment Wetlands

The concept of using wetlands for wastewater treatment emerged in the early 1950s when scientists observed the natural purification ability of marshes and swamps. This led to the first engineered TWs in Germany and the UK, designed to simulate natural wetland processes under controlled conditions.

Over time, the terminology evolved to TWs as recognized by the International Water Association (IWA) to emphasize their purpose as engineered ecological systems for treating wastewater rather than simply constructed habitats (Reddy et al., 2022).

In the 1970s and 1980s, large-scale applications in Europe and North America refined wetland design for municipal wastewater and agricultural effluents. By the 1990s, technological advances introduced subsurface flow systems (Table 1), improving performance and minimizing odor or mosquito issues (Kadlec and Wallace, 2009). In the 21st century, the development of hybrid TWs combined multiple flow regimes (e.g., vertical and horizontal), integrated TWs coupled with bioreactors or UV disinfection, and floating wetland systems suitable for urban and industrial settings.

Table 1. Typologies of treatment wetlands with their advantages and disadvantages

	Description	Advantages	Disadvantages
1. Free Water Surface (FWS) Wetlands (Xin et al., 2022)	Shallow basins where wastewater flows over a planted substrate with a visible water surface; simulates natural marshes.	Low construction and operation costs. Aesthetic and habitat value. Effective for sedimentation and heavy metal removal.	Large land requirement. Odor and mosquito nuisance. Limited efficiency in cold climates.
2. Horizontal Subsurface Flow (HSSF) Wetlands (Ashraf et al., 2020)	Wastewater flows horizontally through a gravel/sand bed planted with macrophytes; water remains below the surface.	High removal efficiency for organics and suspended solids. No odor or insect issues. Minimal maintenance.	May clog if influent is not pretreated. Moderate nitrogen removal efficiency.
3. Vertical Subsurface Flow (VSSF) Wetlands (Bandh and Mushtaq, 2025)	Wastewater is intermittently loaded and percolates vertically through the bed, allowing good oxygen transfer.	Enhanced nitrification and pathogen removal. Requires a smaller area. Effective for high-strength wastewater.	Requires skilled operation and maintenance. Periodic clogging is possible.
4. Hybrid Systems (HSSF + VSSF) (Pérez-Lara et al., 2020)	Combination of vertical and horizontal flow systems in series for complementary treatment.	Maximizes pollutant removal (BOD, N, P). Greater adaptability to different waste streams. Can meet strict effluent standards.	More complex design and higher initial cost. Requires trained personnel.
5. Floating TWs (FTWs) (Joshi et al., 2022)	Artificial rafts with plant roots suspended in water; suitable for ponds, lakes, and reservoirs.	Ideal for retrofitting existing water bodies. Effective nutrient uptake and aesthetic value. No land footprint is required.	Limited hydraulic retention time. Performance depends on climatic conditions.
6. Intensified/Integrated TWs (e.g., TWs + Bioreactor or UV) (Derco et al., 2024)	Combines TWs with mechanical or chemical processes (bioreactors, filters, UV) for advanced treatment.	High and consistent pollutant removal. Suitable for industrial and urban wastewater. Compact footprint.	Higher costs and energy input. Requires technical supervision.

Simple Treatment Wetland System

Experimental research was undertaken by [Cocozza et al. \(2023\)](#) to eliminate contaminants of emerging concern (CEC) and several other pollutants using floating giant reed rhizomes placed inside TWs prepared in vessels. Half the CECs, all the gross parameters, and parental metabolites were reduced in concentration after the treatment application. The TW contained sand of 60 cm layered between two strips of 10 cm gravel at the top and bottom prepared in several containers. Toxic contaminants significantly reduced in concentration at the effluent side post-treatment. It was established that in-vessel TWs can drastically lower the pollutant concentration as a pre-treatment stage of wastewater before transferring it to the main treatment plants for total decontamination. Consequently, TWs alone were found not sufficient to eliminate pollutants, especially the bacterial content of wastewater in fecally polluted effluents.

[Farooqi et al. \(2007\)](#) established two basic categories of TWs: FWS (Free Water Surface) and SSF (Sub-Surface Flow) TWs. In an FWS wetland, the surface is open to the atmosphere, with the water flowing horizontally ([Figure 2a](#)) or vertically through the system ([Figure 2b](#)).

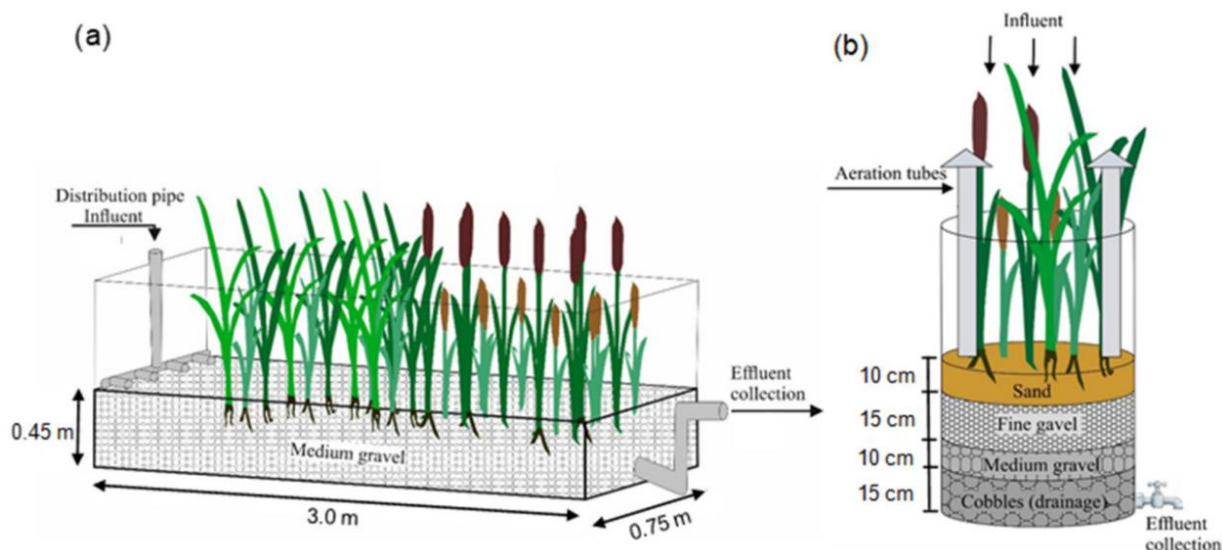


Figure 2. Pilot scale horizontal and vertical flow treatment wetlands (Source: [Gikas et al., 2021](#))

According to the findings of [Zhang and Farahbakhsh \(2007\)](#), SSF wetlands are more efficient than FWS options in eliminating physiochemical parameters from municipal wastewater. Inside Indiana, LaGrange County Metropolis, [García-Pérez et al. \(2011\)](#) were able to establish that corn used as a recirculating vertical flow treatment wetland (VFTW) macrophyte has the capacity to eliminate 99.9% of fecal coliform (FC), 95.6% of TSS, 98.4% of BOD, 94.7% of total Kjeldhal nitrogen (TKN), 95.3% of ammonium nitrogen, 79.5% of total nitrogen (TN), and 75.5% of total phosphorus with a considerable removal of 48.8% potassium.

Baffled Horizontal Flow Treatment Wetland with a Filter Unit

A special TW is used alongside a filter unit to further improve the conventional TW regularly used in wastewater treatment ([Figure 3](#)). In this case, the modified system was called a BHFTW-FU (a baffled horizontal flow Treatment wetland with a filter unit is capable of eliminating total dissolved solids (TDS), lowering the wastewater pH, phenol, and synthetic effluents like the petrochemical wastewater used in the experimental treatment. *Chrysopogon zizanioides* was used as the wetland plant, which provided a flow path up to nine times more than the regular TW. The adjoining filter unit of variable depth and polishing ability minimized the required setup area. Reusable effluent was generated without requiring a post-treatment setup. A highly efficient technique, the BHFTW-FU constituted a novel innovation in the niche of WWT and reuse.

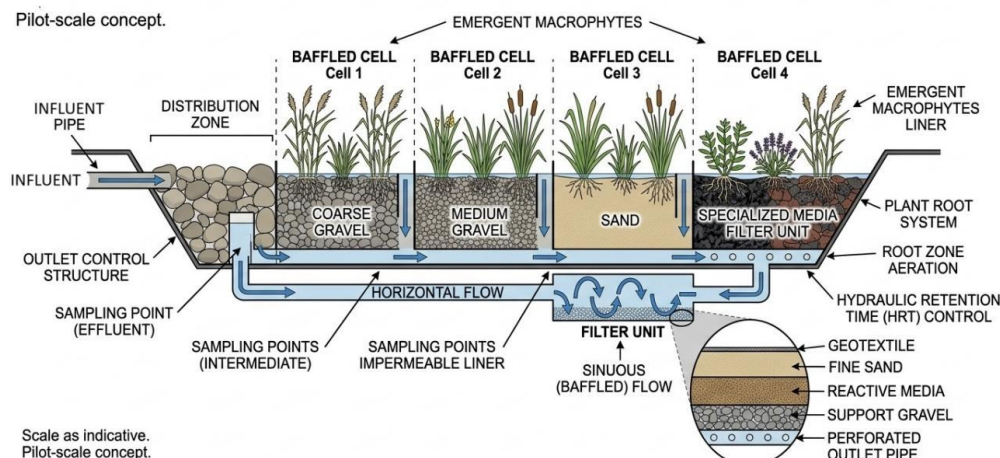


Figure 3. An illustration of the BHFTW-FU (Source: Adapted from Molle et al., 2005)

Ornamental Plants in TWs

According to [García-Ávila et al. \(2023\)](#), countries such as China, Mexico, the United States, Brazil, and India account for a substantial share of global research on the use of ornamental plants in treatment wetlands (TWs) for wastewater treatment. Commonly utilized genera include *Heliconia*, *Canna*, *Zantedeschia*, and *Iris*, which are valued not only for their aesthetic appeal but also for their functional role in pollutant removal. Effluents derived from aquaculture systems can be treated with halophytes, of which their biomass can also serve as metabolites and bioenergy substrates. Ornamental plants were found to be the most efficient in wastewater treatment ([Etesami and Beattie, 2018](#)) in comparison with natural plants and unplanted TWs through the study conducted by [Sandoval-Herazo et al. \(2018\)](#). The system also reduced PO_4^{3-} (up to 92%), NH_4^+ (up to 84%) and total coliform bacteria (up to 99%). According to [Zurita et al. \(2006\)](#), COD was reduced by more than 75% in all cases; BOD and nitrogen were removed by more than 70%, except in one cell; phosphorus was reduced by more than 66% and the dissolved oxygen increased from 0.175 to 5.8 mg/L.

Pharmaceutical and Personal Care Products (PPCPs) Removal Pathways

[Saddoud et al. \(2006\)](#) were able to identify some areas where TWs need a more dedicated exploration especially where other emerging pollutants are becoming peculiar cases of contamination like in the aspect of PPCPs (pharmaceutical & personal care products) ([Loganathan et al., 2023](#)) and pesticide contamination. Schematically, it illustrates the major pathways through which pharmaceutical and personal care products (PPCPs) are removed or transformed ([Figure 4](#)) within TWs. The system operates through a series of interlinked biological, physical, and chemical processes, each contributing to contaminant attenuation and overall effluent polishing.

1. Substrate Adsorption

As PPCP-laden wastewater enters the treatment wetland, the substrate layer (typically gravel, sand, or amended biochar) serves as the first barrier. Hydrophobic or ionizable compounds, such as non-steroidal anti-inflammatory drugs (NSAIDs) and synthetic musks, are adsorbed onto substrate surfaces and biofilms. This process immobilizes pollutants, reducing their mobility and preventing groundwater infiltration. Biochar and zeolite-amended substrates enhance this step by offering higher surface area and adsorption capacity.

2. Plant Uptake and Phytodegradation

Macrophytes such as *Phragmites australis*, *Typha latifolia*, and *Canna indica* play a central role in PPCP removal through phyto uptake. Their extensive root systems absorb soluble compounds like ibuprofen, sulfamethoxazole, and triclosan. Within plant tissues, enzymatic reactions (oxidation and conjugation) convert these substances into less toxic metabolites, a process known as phytodegradation. The plants also release oxygen into the rhizosphere, supporting aerobic microbial activity around their roots.

3. Microbial Biodegradation

The rhizosphere zone of the wetland supports a dense community of bacteria and fungi that drive aerobic and anaerobic degradation of PPCPs. Microbes use these organic contaminants as energy or carbon sources, breaking them down through enzymatic reactions such as hydroxylation, demethylation, and ring cleavage. Species of *Pseudomonas*, *Bacillus*, and *Acinetobacter* are often associated with the biodegradation of antibiotics and hormones. In hybrid systems, alternating aerobic (vertical flow) and anaerobic (horizontal flow) environments enhance degradation efficiency.

4. Photolysis and Photo-oxidation

At the water surface, solar radiation initiates photolytic decomposition of photosensitive PPCPs like carbamazepine and diclofenac. The presence of dissolved oxygen facilitates photo-oxidation, producing reactive oxygen species (ROS) that further degrade persistent compounds. Floating TWs maximize this effect by increasing light exposure and turbulence at the water-air interface.

5. Sludge and Biofilter Application as Fertilizer

Solid residues and biomass collected from TWs, particularly plant litter, root debris, and substrate sludge, contain adsorbed nutrients and trace PPCP residues. After stabilization (through drying or composting), these materials can be safely repurposed as organic fertilizers or soil conditioners. This not only supports nutrient recycling but also embodies circular-economy principles, converting waste by-products into valuable agricultural inputs while maintaining environmental safety.

PPCP removal in TWs occurs through a synergistic combination of:

- adsorption onto the substrate and biofilms,
- plant uptake and enzymatic degradation,
- microbial metabolism in rhizosphere zones,
- photolytic and oxidative decomposition at the surface, and
- resource recovery through sludge and biofilter reuse.

These integrated pathways transform TWs into nature-based bioreactors that simultaneously achieve wastewater purification and resource recovery. The diagram thus encapsulates the dynamic, multi-mechanistic nature of PPCP treatment, reinforcing the paper's aim to promote sustainable, low-energy, and eco-engineered solutions for emerging pollutant management in developing regions.

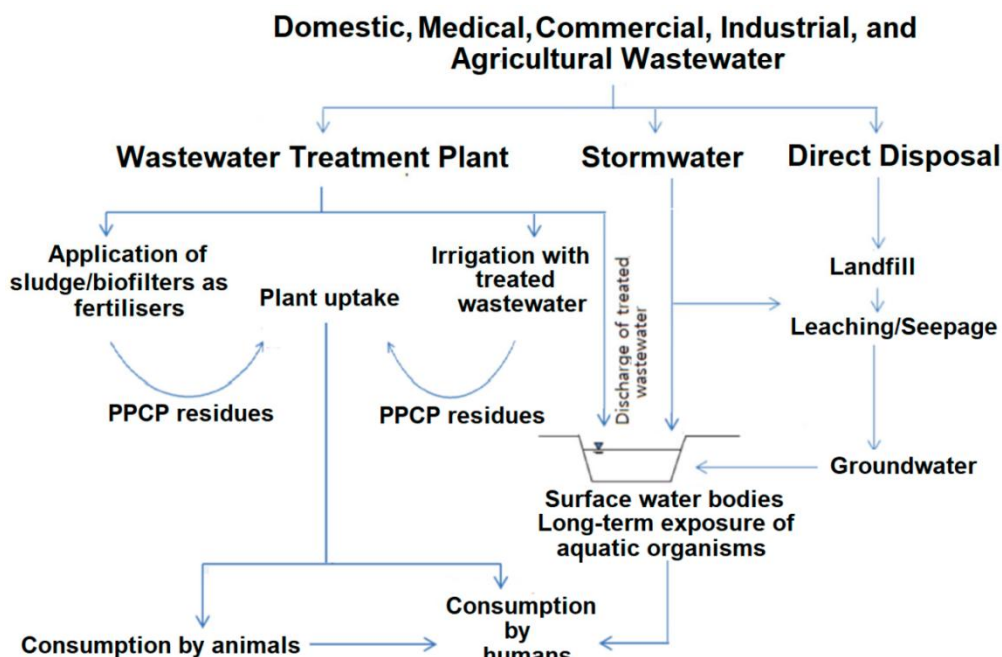


Figure 4. PPCPs and their removal processes (Source: Loganathan et al., 2023)

Halophytes and Their Benefits

Halophytes are salt-tolerant plants that can grow and thrive in saline or brackish environments where most conventional vegetation cannot survive. These plants possess unique physiological and biochemical mechanisms such as salt secretion through specialized glands, ion compartmentalization within vacuoles, and osmotic adjustment that allow them to tolerate high salinity levels (Hassan et al., 2020). In TWs, halophytes play a crucial role in removing nutrients, heavy metals, and organic pollutants from saline and domestic wastewater. Common examples of halophytes used in TWs include *Spartina alterniflora*, *Salicornia europaea*, *Phragmites australis*, *Atriplex halimus*, and *Distichlis spicata*. Their natural resilience to harsh water chemistry and their robust growth make them ideal macrophytes for constructed and hybrid wetland systems.

Benefits of Halophytes in TWs

1. Enhanced Nutrient Uptake

Halophytes efficiently absorb and store nitrogen (N) and phosphorus (P) from wastewater, thus preventing eutrophication of downstream water bodies. Their high biomass productivity enables the continuous removal of nutrients even under saline or nutrient-rich conditions (De Lange et al., 2013).

2. Tolerance to Salinity and Toxic Compounds

These plants can thrive in wastewater streams with elevated concentrations of salts, ammonia, and trace metals. This makes halophyte-based TWs particularly suitable for saline industrial effluents, aquaculture discharge, and municipal wastewater in coastal or arid regions (Klomjek and Nitorisavut, 2005).

3. Heavy Metal Accumulation and Phytoremediation

Many halophytes, such as *Phragmites australis* and *Atriplex halimus*, have the ability to uptake, sequester, or transform heavy metals like cadmium, lead, zinc, and copper. This contributes to the detoxification of contaminated effluents and sediments through phytoremediation (Fountoulakis et al., 2017).

4. High Biomass Yield for Resource Recovery

Substantial biomass produced by halophytes can be harvested and repurposed for bioenergy generation (biogas or bioethanol), animal fodder, organic compost, or soil conditioners. This aligns with circular economic principles by transforming waste into valuable resources (Hassan et al., 2020).

5. Improved System Stability and Aesthetic Value

Deep halophyte root systems improve substrate aeration, hydraulic conductivity, and biofilm support, which enhance microbial degradation processes. In addition, their lush growth contributes to the aesthetic and ecological value of TW installations, fostering biodiversity (De Lange et al., 2013).

6. Adaptability to Arid and Coastal Climates

Halophyte-based TWs are particularly advantageous for Sub-Saharan Africa, where salinization, drought, and limited freshwater resources are prevalent. Their resilience allows for year-round wastewater polishing under extreme environmental conditions (Hassan et al., 2020).

Halophytes offer a multifunctional approach to wastewater management by combining resilience, remediation, and resource recovery. Their integration into TWs enhances system efficiency, promotes sustainable reuse of saline effluents, and contributes to the overall goal of achieving freshwater conservation through natural, low-cost technologies.

Anaerobic and Membrane Bioreactors Combined with TWs

Domestic wastewater was treated by Ali et al. (2018) in India using an anaerobic bio-reactor (ABR), two hybrid TWs and finally a free water surface (FWS) designed for each of the hybrid TWs. Over 94% of pathogens eliminated from the wastewater were microorganisms, with 93% bacteria removed by system II (which was the horizontal sub-surface flow (HSSF) TW setup). The vertical sub-surface flow (VSSF) TW was the system I hybrid setup, which eliminated 94% of the bacterial pollutants. System II removed 89% of total suspended solids (TSS), 69% of nitrogen, 82% of biological oxygen demand (BOD) and 78% of chemical oxygen demand (COD). Conversely, System I reduced 79%, 63%, 81%, and 80% of TSS, Nitrogen, BOD, and COD, respectively. Conclusively, the ABR, the two hybrid TWs, the two FWS setups all showed significance in decontaminating the wastewater from bacteria, solids, and organic content.

Fecal sludge was treated within university campuses in Brazil using a combination of horizontal, floating, and vertical TWs, and anaerobic reactors (Figure 5), which were considered safe and clean alternative technologies in the ecosystem (Purnell et al., 2016). Four different macrophytes were used in the TWs: Papyrus, *Hymenachne grumosa*, *Lemna minor* spp., and *Vetiveria zizanoides*. A 3-day hydraulic retention time was allotted for the anaerobic reactor treatment method, while a total of 7 days of retention time was applied to the TW section. MBRs proved their high capacities in eliminating pathogens and bacterial threats in wastewater (Harb and Hong, 2017a, 2017b). The evaluation of MBRs has been researched extensively using culture-based techniques (Table 2).

TWs with Trophic Ponds and Bio-Filtration Technique

A green, bio-compatible, eco-friendly, sustainable, simple, and cost-efficient method of treating wastewater contaminated with organic compounds or heavy metals is the bio-filtration technique (Figure 5). Pauwels et al. (2006) conducted a study using this efficient method to eliminate the pollutants present in municipal wastewater. Algae, yeast, bacteria, fungi, and plants were biological sources that were used to achieve this goal naturally without any introduction of chemicals into the wastewater.



Figure 5. Graphical illustration of a TW and anaerobic setup (Source: da Silva et al., 2021)

In the case of da Silva et al. (2021) they combined the TW treatment option with a bio-filter setup and a trophic biology pond similar to that of Winward et al. (2008) for the elimination of harmful microbes and carbon through metabolism and temperature resistance. A study of trophic salt ponds was conducted by Tenkeu et al. (2021) to determine the mesohaline and hyperhaline properties of the wetlands, which was beneficial to the aquatic life and micro-organisms within the habitat.

Table 2 summarizes the comparative performance of different MBR systems applied to domestic, municipal, and industrial wastewater treatment. Each system is defined by its membrane type, nominal pore size, influent characteristics, and detection methods used to quantify microbial contamination (e.g., *E. coli*, fecal coliforms, *Pseudomonas aeruginosa*). As shown in Table 2, aerobic and anaerobic membrane bioreactors demonstrate exceptional microbial removal efficiency, achieving up to 7 log reductions for common pathogens. Systems utilizing smaller pore membranes ($\leq 0.05 \mu\text{m}$) and integrated with anaerobic pretreatment consistently outperform stand-alone configurations. These results reinforce the viability of hybrid MBR treatment wetland systems as sustainable wastewater treatment technologies capable of meeting reuse standards, especially in resource-limited regions of Sub-Saharan Africa.

Key observations from the table include:

1. **High Microbial Removal Efficiency**

Most MBR systems achieved log removal values (LRVs) between 5.0 and 7.0, indicating up to 99.999% reduction in microbial loads. For instance, aerobic MBRs with $0.04 \mu\text{m}$ pore size recorded LRVs > 6.5 for total and fecal coliforms, reflecting near-complete pathogen elimination.

2. **Effect of Membrane Type and Pore Size**

Smaller pore membranes ($0.03\text{--}0.05 \mu\text{m}$) consistently perform better than larger-pore configurations, emphasizing the importance of membrane selectivity and filtration pressure in achieving high-quality effluent.

3. **Influence of Wastewater Type**

MBRs treating municipal wastewater exhibit more consistent pathogen removal compared to industrial or greywater, which can have variable organic loads. The presence of surfactants and low nutrients in greywater occasionally reduces microbial growth and thus lowers degradation rates.

4. **Integrated System Advantage**

The combined use of anaerobic bioreactors (ABRs) with TWs further enhances treatment performance. The ABR pre-treats high-strength effluents, reducing organic load before entering the MBR or TW, resulting in improved filtration efficiency and a longer membrane lifespan.

5. **Sustainability Implications**

The high pathogen removal demonstrated by these systems supports their integration into low-cost, decentralized wastewater reuse frameworks in developing regions. When combined with TWs, MBRs provide a robust hybrid solution that achieves both microbial safety and water quality compliance for reuse in irrigation and aquaculture.

Applicability of TWs in Sub-Saharan Africa

TWs are particularly well-suited for Sub-Saharan Africa (SSA) due to their low cost, low energy, and low maintenance characteristics, attributes that align with the socioeconomic realities of many communities in the region.

Most areas in SSA face constraints such as limited financial resources, unreliable electricity, and low technical capacity for operating complex wastewater treatment plants. In this context, TWs provide a practical alternative that leverages natural processes and local materials to achieve wastewater purification and reuse.

Furthermore, TWs are adaptable to rural and peri-urban lifestyles, where land availability is less restrictive than in dense urban centers. They can be integrated into community-based sanitation systems, small housing clusters, schools, and agro-industrial facilities. Their decentralized nature reduces dependence on centralized sewer networks, an advantage in regions where such infrastructure is limited or absent.

The habits of inhabitants also favor TW adaptability. For instance, greywater from washing and bathing can be separated easily at the household level and treated on-site using small-scale horizontal or vertical flow wetlands. In many SSA communities, there is cultural acceptance of wastewater reuse for irrigation, particularly for non-edible crops or tree plantations. Therefore, TWs not only treat wastewater but also enable water recycling and nutrient recovery, supporting local agriculture and food security.

TWs represent an adaptable, community-oriented solution for wastewater management in Sub-Saharan Africa. Their alignment with local socioeconomic conditions, use of indigenous materials, and capacity for nutrient recovery and reuse make them ideal for sustainable sanitation strategies. However, successful implementation depends on the policy support, capacity building, and community engagement to ensure long-term operation and acceptance.

Table 2. Performance of aerobic and anaerobic membrane bioreactors (MBRs) in the removal of microbial indicators, mostly using a culture-based plate count detection method. NA: Not Applicable; ND: Not Detected

System type	Wastewater; Membrane pore size	Indicator/Pathogen in Influent (CFU/100 mL)		LRV	Reference
Aerobic MBR	High-strength greywater; 0.05 μm	Total Coliform	~107.4	>7	Winward et al. (2008)
		<i>E. coli</i>	~103.8	NA	
		<i>Enterococci</i>	~102.7	2.6	
		Clostridia	~102.9	2.8	
		<i>P. aeruginosa</i>	~107	6.5	
Aerobic MBR	Municipal Wastewater; 0.04 μm	Total coliform	NA	5.5	Zhang and Farahbakhsh (2007)
		Fecal coliform	~107	6.5	
Aerobic MBR	Municipal Wastewater; 0.04 μm	Total coliform	~107	5.5	Alaboud (2015)
		Fecal coliform	~104	2.6	
Aerobic MBR	Municipal Wastewater; 0.04 μm	Total coliform	~106 to 108	4.7-5.1	Bolzonella et al. (2010)
		<i>E. coli</i>	NA	ND	
Aerobic MBR	Industrial Wastewater; 0.04 μm	Total coliform	NA	6.5	Branch et al. (2016)
		<i>E. coli</i>	NA	5.5	
		<i>C. perfringens</i>	NA	5.0	
Aerobic MBR	Municipal Wastewater; 0.04 μm	Fecal coliform	~107	6.9	Purnell et al. (2016)
		<i>Enterococci</i>	~106	6.1	
Aerobic MBR	Municipal Wastewater; 0.03-0.1 μm	Total coliform	~107	5.8-6.9	Hirani et al. (2010)
		Fecal coliform	~106	5.4-6.0	
Aerobic MBR	Municipal Wastewater; 0.03-0.2 μm	Total coliform	~106 to 108	5.5-6.7	Hirani et al. (2012)
		Fecal coliform	~106 to 107	5.3-6.5	
AAO MBR	Combined wastewater: Greywater and Kitchen wastewater	Fecal coliform	~104.8	6.2	Zhou et al. (2015)
		<i>E. coli</i>	~103.5	4.7	
		<i>Salmonella</i>	~101.5	2.3	
		<i>Shigella</i>	~100.8	2.6	
AAO MBR	Greywater; 0.45 μm	Fecal coliform	~104	0.5	Jong et al. (2010)
		<i>E. coli</i>	~104	0.7	
		<i>Staphylococcus</i>	~104	0.1	
		<i>Salmonella</i>	~104	0.1	
AAO MBR	Municipal wastewater; 0.4 μm	<i>E. coli</i>	~106	6.1	Marti et al. (2011)
		Clostridia	~105.6	4.8	

CONCLUSION

This review demonstrates that treatment wetlands (TWs), when designed and integrated within appropriate wastewater treatment lines, constitute a robust, low-energy, and environmentally sustainable solution for wastewater purification and freshwater conservation. By shifting from the traditional concept of constructed wetlands to the IWA-preferred term TWs, the paper reinforces the view of TWs as engineered ecological systems specifically optimized for pollution control and resource recovery.

A key conclusion of this work is that source separation and tailored treatment lines, such as those for greywater, urine, and feces, significantly enhance treatment efficiency. When these treatment lines are coupled with TWs, pollutant loads are reduced prior to wetland entry, thus improving hydraulic performance, minimizing clogging, and extending system lifespan. This integrated approach enables TWs to function as effective secondary or tertiary treatment units rather than overloaded, stand-alone systems.

The review further confirms that TWs can remove not only conventional pollutants (organic matter, nutrients, and pathogens) but also emerging contaminants, including pharmaceuticals and personal care products (PPCPs). The simultaneous action of substrate adsorption, plant uptake, microbial biodegradation, photolysis, and biofilter or sludge reuse transforms TWs into multifunctional bioreactors that align with circular-economy principles. This capacity is particularly relevant in regions where advanced mechanical treatment technologies are economically or technically infeasible.

From a typological perspective, the evolution from free water surface systems to subsurface, hybrid, floating, and intensified TWs reflects increasing design sophistication and adaptability. Hybrid and integrated systems consistently show superior performance, especially where stringent effluent standards or limited land availability apply. However, simpler horizontal and vertical subsurface flow wetlands remain highly appropriate for decentralized applications.

Importantly, the paper establishes that TWs are exceptionally suited to Sub-Saharan Africa, where water scarcity, rapid urbanization, limited infrastructure, and socioeconomic constraints prevail. Their compatibility with local habits, availability of land in peri-urban and rural settings, minimal energy demand, and potential for community participation make TWs a realistic and scalable wastewater management option. The case examples from Nigeria, South Africa, Kenya, and Ghana confirm both technical feasibility and socio-environmental benefits, despite challenges related to land pressure, seasonal variability, and institutional capacity.

In conclusion, TWs, when embedded within well-designed treatment lines, represent a strategic nature-based solution for addressing wastewater pollution, freshwater scarcity, and public health risks. Their successful deployment depends on sound design, policy support, community engagement, and capacity building. Future research should focus on performance optimization under tropical climates, the long-term fate of emerging contaminants, and the integration of TWs into national water and sanitation frameworks.

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