



Impact of Wastewater on the Soil–Plant–Atmosphere Interface: Challenges and Remediation Approaches

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ABSTRACT

Wastewater reuse in agriculture has emerged as both a necessity and an opportunity in the face of global freshwater scarcity. While its use can improve water availability and reduce dependency on synthetic fertilizers, wastewater—especially when untreated—poses significant challenges across the soil–plant–atmosphere interface (SPAI). This review explores the complex interactions and consequences of wastewater irrigation, examining impacts on soil structure, microbial communities, nutrient balance, and heavy metal accumulation. It further analyzes physiological stress responses in crops, food safety concerns, and disruptions to evapotranspiration, greenhouse gas emissions, and plant–microbe signaling. The article reviews a range of remediation strategies, from low-cost treatment technologies (e.g., constructed wetlands, biochar filtration) to soil amendments, crop rotation, and precision irrigation. Emphasis is placed on integrated, context-specific approaches that combine technical, agronomic, and institutional solutions. Long-term sustainability of wastewater reuse depends on effective monitoring, risk mitigation, and adaptive policies that address emerging threats like microplastics and antibiotic resistance. The review concludes by identifying research priorities focused on system-level feedbacks within the SPAI and advocates for wastewater reuse strategies aligned with circular economy, food safety, and climate-smart agriculture goals.

Keywords: Wastewater, soil–plant–atmosphere, heavy metals, phytoremediation, microplastics, soil health.

INTRODUCTION

Water scarcity and resource degradation have driven an increasing global interest in the reuse of wastewater for agricultural irrigation. As urbanization, industrialization, and population growth place rising demands on freshwater, wastewater—both treated and untreated—has become a significant alternative source for sustaining crop production, especially in arid and semi-arid regions (FAO, 2023). While wastewater reuse offers certain agronomic benefits, including nutrient recycling and water availability during dry seasons, it also presents critical challenges that extend beyond crop productivity, affecting soil quality, ecosystem functioning, and atmospheric interactions. These interconnected effects are most evident at the soil–plant–atmosphere interface (SPAI), a dynamic zone where physical, chemical, and biological processes converge.

Globally, more than 20 million hectares of farmland are estimated to be irrigated with wastewater, a figure that is expected to grow as climate change accelerates freshwater depletion and disrupts rainfall patterns (Qadir et al., 2022). Municipal wastewater, industrial effluents, and agricultural drainage water are all commonly reused for irrigation, often with little or no treatment—particularly in low- and middle-income countries. Although these wastewaters contain essential nutrients such as nitrogen, phosphorus, and potassium, they also harbor a diverse array of contaminants, including heavy metals, pharmaceuticals, pathogens, surfactants, and microplastics (Suthar et al., 2022). These compounds, when repeatedly applied to soil–plant systems, can trigger cascading effects that challenge not only agronomic outcomes but also ecological sustainability and human health.

The soil–plant–atmosphere continuum is especially vulnerable to such disturbances. Contaminants in wastewater can alter soil microbial activity, disrupt root architecture, reduce plant gas exchange, and modify evapotranspiration patterns. Moreover, the accumulation of toxicants and salinity in soil can impair hydraulic conductivity, water retention, and nutrient cycling—all of which are central to plant growth and microclimate

regulation. Such disruptions can feed back into broader environmental processes, including greenhouse gas emissions from soil, volatilization of ammonia, and aerosol formation—extending the consequences of wastewater irrigation from the field to the atmosphere (Zhao et al., 2023).

While many studies have evaluated the impacts of wastewater on soil or crops in isolation, fewer have addressed the systemic effects across the SPAI, which is essential for understanding long-term sustainability. Additionally, much of the available research focuses on short-term physiological or yield responses, often overlooking the cumulative effects of contaminants on soil structure, microbial networks, and plant-atmosphere feedbacks. For instance, the rise of microplastic contamination in wastewater effluent is an emerging threat that compromises soil porosity, root-soil contact, and microbial symbioses—factors not adequately captured by conventional soil or crop assays (Li et al., 2022).

Despite these risks, wastewater irrigation can be made more sustainable through appropriate treatment technologies, site-specific management, and adaptive remediation strategies. Constructed wetlands, filtration through biochar or zeolites, and biological degradation systems are among the tools available to reduce the toxic load of irrigation water. Simultaneously, adopting salt-tolerant or heavy metal-accumulating crops, rotating plant species, and applying organic amendments to buffer contaminant impacts are increasingly recognized as complementary field-level approaches. These measures, however, require a systems-thinking approach that accounts for the SPAI as a whole, rather than focusing narrowly on one component.

The goal of this review is to synthesize current knowledge on the impacts of wastewater irrigation across the soil–plant–atmosphere interface and evaluate challenges and remediation strategies from a holistic agroecological perspective. It brings together findings from soil science, plant physiology, environmental toxicology, and atmospheric chemistry to highlight both the threats and potential of wastewater reuse. By framing wastewater impacts at the interface level, this review aims to inform sustainable water reuse policies, enhance agroecosystem resilience, and support circular approaches to agricultural resource management in a warming and water-scarce world.

Composition and Sources of Wastewater

The composition of wastewater used in agriculture varies widely depending on its source, season, and level of treatment. It typically includes a complex mixture of organic and inorganic compounds, nutrients, pathogens, and emerging contaminants. Understanding these components is critical to assess their behavior in the soil–plant–atmosphere interface (SPAI), predict risks, and develop mitigation strategies. Wastewater may originate from municipal (domestic), industrial, or agricultural sources, each with distinct chemical and biological signatures that influence its impact on agroecosystems.

Municipal wastewater, the most commonly reused category, generally contains high levels of organic matter (e.g., proteins, carbohydrates, fats), human pathogens (e.g., *E. coli*, *Salmonella*, *Giardia*), pharmaceutical residues (e.g., antibiotics, hormones), and nutrients such as nitrogen and phosphorus. It is often used untreated or partially treated in peri-urban agriculture, where water scarcity compels farmers to rely on non-conventional sources. Nutrients present in municipal effluent can enhance crop growth, but the risk of pathogen transmission and antibiotic resistance propagation poses serious human and animal health concerns (Kumar et al., 2022; WHO, 2023).

Industrial wastewater is highly variable and site-specific, with its composition determined by the type of industry, raw materials, and effluent management practices. Common pollutants include heavy metals (e.g., cadmium, lead, mercury, chromium), volatile organic compounds (VOCs), synthetic dyes, hydrocarbons, and in many cases, high levels of salinity or acidity. Tannery, electroplating, textile, mining, and paper industries are major contributors to toxic industrial wastewater. Long-term application of such water may lead to irreversible soil contamination, accumulation of toxicants in edible crops, and decline in microbial activity essential for soil health (Rathod et al., 2023; Zhang et al., 2023).

Agricultural runoff and drainage water, while technically not industrial, represent another wastewater stream used for irrigation in water-scarce regions. These waters often contain pesticide residues, nitrate-nitrogen, phosphates, and sediments, contributing to soil acidification, leaching, and algal blooms in surrounding water bodies. In rice-wheat systems of South Asia and irrigated cotton zones of Central Asia, such reuse practices have led to salinization and soil crusting (Bhattarai et al., 2022).

A key concern across all wastewater types is the presence of emerging contaminants—chemicals that are not routinely monitored but may have ecological and health impacts. These include pharmaceuticals, personal care products, microplastics, and antibiotic-resistant genes (ARGs). Studies have found that long-term application of municipal wastewater containing antibiotics and ARGs can alter soil microbial diversity, suppress beneficial symbiotic bacteria, and promote resistant strains that threaten public health (Gatica & Cytryn, 2022). Similarly, microplastic particles (<5 mm in diameter), often present in urban wastewater, can affect soil porosity, root penetration, and rhizosphere microbial interactions (Li et al., 2022).

Quantifying wastewater composition relies on a range of physicochemical indicators. Key parameters include:

- **Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD):** indicators of organic matter load and oxygen depletion potential;

- **Total Dissolved Solids (TDS) and Electrical Conductivity (EC):** indicators of salinity and potential soil sodicity issues;
- **pH and alkalinity/acidity:** affect nutrient solubility and soil buffering capacity;
- **Heavy metal concentration (e.g., Cd, Pb, Zn):** determine bioaccumulation risk and long-term soil toxicity;
- **Coliform and pathogen counts:** assess microbiological safety;
- **Nutrient concentrations (NO_3^- , NH_4^+ , PO_4^{3-}):** influence fertilizer value and eutrophication risk.

The seasonal variation of wastewater composition is also important. During the monsoon or rainy season, effluent is often diluted, reducing contaminant concentrations. Conversely, in dry seasons, concentrated wastewater with reduced flow can increase salinity, heavy metal load, and pathogen concentrations, especially in unregulated discharge systems (Sharma et al., 2023). These dynamics must be factored into irrigation planning to avoid acute phytotoxicity or soil structure damage.

Regional disparities further shape the composition and impact of wastewater. In high-income countries, wastewater is often treated to secondary or tertiary levels, reducing organic and microbial loads before reuse. In contrast, many low- and middle-income countries lack infrastructure or governance to enforce discharge limits, resulting in widespread use of raw sewage or untreated industrial effluent. Consequently, the risks and benefits of wastewater reuse in agriculture are highly context-dependent and require site-specific assessments (FAO, 2023; Qadir et al., 2022).

Ultimately, the reuse of wastewater in agriculture cannot be decoupled from its chemical complexity and ecological consequences. While nutrient-rich wastewater may reduce fertilizer needs and provide a dependable water source, the simultaneous exposure of soils, crops, and atmospheric components to diverse contaminants introduces persistent, and often underappreciated, risks. A clear understanding of wastewater composition is thus the foundation for sustainable irrigation practices, safe food production, and remediation strategy design (Table 1).

Table 1: Summary of Wastewater Constituents and Their Effects on SPAI Components

Wastewater Constituent	Soil Impact	Plant Impact	Atmospheric Impact
Heavy metals (e.g., Cd, Pb)	Enzyme inhibition, microbial toxicity	ROS generation, yield loss	Bioaccumulation and volatilization
Microplastics	Reduced porosity, pollutant adsorption	Impaired root function	Altered GHG profiles
Pathogens	Contamination risk	Leaf contact infection	Airborne aerosol formation
Nutrients (N, P)	Fertility boost, but potential imbalance	Growth stimulation or toxicity	Increased N_2O , NH_3 emissions
Surfactants, antibiotics	Microbial community shift	Hormonal disruption	Impaired quorum sensing

Impacts on Soil Health and Properties

Soil functions as both a filter and a reservoir in wastewater-irrigated systems, absorbing nutrients and contaminants alike. While short-term use of nutrient-rich wastewater may appear beneficial, continuous application—especially of untreated or poorly treated effluents—can substantially degrade soil health. These impacts are multifaceted, affecting physical, chemical, and biological properties of soil and ultimately altering its capacity to sustain crop productivity, regulate water, and support microbial ecosystems. Evaluating these changes at the soil–plant–atmosphere interface (SPAI) is essential for understanding the long-term sustainability of wastewater reuse in agriculture.

Wastewater irrigation often leads to deterioration of soil physical properties. High levels of total dissolved solids (TDS), sodium, and suspended particles in effluents can cause soil dispersion, reducing aggregate stability and pore connectivity. This results in reduced infiltration rates, surface sealing, and compaction, especially in clay-rich soils. Over time, these changes limit root penetration, water retention, and aeration—affecting both plant health and microbial activity (Zhao et al., 2023). The use of wastewater high in sodium relative to calcium and magnesium—characterized by high Sodium Adsorption Ratio (SAR)—can exacerbate sodicity, leading to crust formation and hard-setting behavior in soils (Li et al., 2022).

Chemically, wastewater alters the nutrient balance and ionic composition of soils. While municipal wastewater may initially enrich soils with macronutrients like nitrogen (N), phosphorus (P), and potassium (K), prolonged application often leads to nutrient imbalance, soil acidification, or excessive alkalinity, depending on effluent source. Repeated inputs of nitrate and ammonium can acidify soils, particularly in poorly buffered systems, while untreated wastewater with high pH can elevate soil alkalinity and interfere with micronutrient availability (Rathod et al., 2023). Elevated electrical conductivity (EC) from dissolved salts in wastewater contributes to secondary salinization, reducing plant water uptake and exacerbating osmotic stress in crops.

A key concern in wastewater-irrigated soils is the accumulation of heavy metals and trace elements, particularly in regions where industrial effluents are discharged without regulation. Metals such as cadmium (Cd), lead (Pb), chromium (Cr), zinc (Zn), and arsenic (As) are persistent in soils and bind strongly to clay and organic matter fractions. These toxic elements can remain in the root zone for years, posing risks to soil biota, entering food

chains, and diminishing soil fertility through enzyme inhibition and microbial toxicity (Zhang et al., 2023; Suthar et al., 2022).

The biological impacts of wastewater on soil are equally significant. Short-term inputs of organic matter and nutrients can stimulate microbial activity and biomass. However, long-term exposure to toxic compounds—including heavy metals, antibiotics, surfactants, and microplastics—often leads to microbial community shifts, decline in functional diversity, and suppression of beneficial organisms, such as nitrogen-fixing bacteria and mycorrhizae. Enzymatic activities involved in nutrient cycling (e.g., urease, phosphatase, dehydrogenase) tend to decline under heavy metal stress, disrupting the soil's biological buffering capacity (Gatica & Cytryn, 2022; Sharma et al., 2023).

Organic matter dynamics in wastewater-irrigated soils are complex. While wastewater can supply labile carbon and stimulate microbial mineralization, the decomposition of certain recalcitrant organic compounds (e.g., synthetic detergents, hydrocarbons, plastics) is slow, leading to accumulation of non-biodegradable residues in soil. These residues alter the soil's carbon:nitrogen ratio, adsorb to soil particles, and may act as long-term pollutants affecting both microbial metabolism and root development (Bhattarai et al., 2022).

Another emerging area of concern is the impact of microplastics and nanoplastics introduced via wastewater. These particles interfere with soil structure, reduce aggregate stability, and have been found to reduce earthworm activity, nematode diversity, and microbial respiration. Their hydrophobic surfaces adsorb organic contaminants and metals, creating “pollutant cocktails” that amplify toxicity in the rhizosphere (Li et al., 2022). Such complex interactions remain underexplored in the context of soil health but represent a growing challenge for wastewater reuse.

Despite these negative trends, the impacts of wastewater on soils are not universally detrimental. When properly treated and monitored, wastewater can support soil fertility by replenishing organic matter, enhancing nutrient availability, and improving microbial activity—particularly in degraded or nutrient-poor soils. Treated effluent with balanced nutrient loads and minimal contaminant levels has been shown to improve crop yields and restore organic matter levels in semi-arid regions of the Middle East and North Africa (FAO, 2023).

Therefore, the effects of wastewater on soil health are highly context-dependent, shaped by wastewater composition, soil type, irrigation frequency, crop selection, and management practices. Sustainable reuse must consider site-specific risk thresholds for salinity, heavy metals, and microbial contaminants, while investing in treatment and soil remediation strategies tailored to local agroecological conditions.

Effects on Plant Physiology and Crop Productivity

The use of wastewater in irrigation significantly affects plant physiological processes and overall crop productivity, with outcomes that range from beneficial to detrimental depending on the type, concentration, and frequency of wastewater application. While nutrient-rich effluents can support growth in nutrient-poor soils, the simultaneous presence of toxicants—such as heavy metals, pathogens, organic pollutants, and salinity—can disrupt plant development, impair physiological functioning, and pose serious food safety concerns. These effects are mediated not only at the cellular level but also through interactions within the soil–plant–atmosphere interface (SPAI), where water, nutrient, and contaminant exchanges converge.

Wastewater's nutrient content, particularly in municipal effluents, can initially stimulate plant growth. Nitrogen and phosphorus in wastewater promote chlorophyll synthesis, leaf expansion, and photosynthetic rate, often leading to increased biomass and yield in the short term (Qadir et al., 2022). However, imbalanced nutrient ratios, excess ammonium or nitrate, and micronutrient deficiencies (e.g., Zn, Fe) can eventually lead to nutrient toxicity or antagonistic effects that compromise plant health. For example, high ammonium concentrations can inhibit root elongation and alter cytoplasmic pH, while excessive phosphorus may induce zinc deficiency, particularly in calcareous soils (Rattan et al., 2022).

One of the most critical concerns with wastewater irrigation is the uptake and accumulation of heavy metals in plant tissues. Plants irrigated with water containing cadmium (Cd), lead (Pb), mercury (Hg), or arsenic (As) often show inhibited seed germination, reduced root and shoot length, chlorosis, and oxidative stress. Heavy metals disrupt enzymatic activity, damage chloroplast structures, and generate reactive oxygen species (ROS), leading to lipid peroxidation and membrane damage (Sharma et al., 2023). Accumulation of Cd and Pb in edible parts of leafy vegetables, such as spinach, lettuce, and cabbage, has been widely reported and often exceeds WHO/FAO permissible limits, raising food safety concerns for consumers (Bhattarai et al., 2022).

Wastewater irrigation can also disrupt plant water relations and gas exchange. High salt concentrations in wastewater create osmotic stress that reduces root water uptake and leads to stomatal closure, thereby decreasing transpiration and photosynthetic rates. Sodium toxicity can interfere with potassium uptake, impairing metabolic processes such as carbohydrate transport and protein synthesis. In tomato, lettuce, and maize, wastewater-induced salinity has been linked to leaf burn, premature senescence, and reduced harvest index (Rai et al., 2023).

Moreover, contaminants in wastewater can impact plant hormonal balance and signaling pathways, especially auxin and abscisic acid (ABA) pathways. Disruption of hormone homeostasis alters root architecture, branching patterns, and nutrient acquisition efficiency. For example, plants exposed to wastewater containing surfactants or

pharmaceuticals may exhibit abnormal root growth or reduced lateral root formation, affecting their anchorage and nutrient access (Li et al., 2022).

Another area of concern is the bioaccumulation and translocation of pollutants from roots to shoots and edible organs. Uptake mechanisms for heavy metals often mimic those of essential nutrients—for example, Cd competes with Zn, and arsenate mimics phosphate—making selective exclusion difficult for plants. Long-term irrigation with contaminated wastewater can lead to persistent buildup of these metals in grain, fruit, or tubers, jeopardizing food security and marketability (Ghosh et al., 2023).

In addition to abiotic stress, wastewater affects plant–microbe interactions in the rhizosphere. Beneficial associations, such as those with arbuscular mycorrhizal fungi (AMF) or nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*), are often suppressed by heavy metal or antibiotic contamination. This reduction in symbiotic efficiency affects nutrient cycling, nitrogen fixation, and plant resilience to environmental stressors (Gatica & Cytryn, 2022). In legume crops, wastewater has been shown to reduce nodule formation and nitrogenase activity, thereby decreasing protein content and yield.

Despite these negative effects, positive responses have also been reported under controlled application of treated wastewater. In several arid and semi-arid regions, judicious use of treated municipal wastewater has led to increased yields in cereals (e.g., wheat, barley), vegetables (e.g., onion, tomato), and forage crops, particularly when supplemented with soil amendments to mitigate salinity and metal uptake. The key lies in the balance between nutrient supply and contaminant risk, as well as the crop's tolerance threshold (FAO, 2023).

Importantly, plant response to wastewater irrigation is highly species-specific. Leafy vegetables and root crops tend to accumulate more heavy metals than grains or oilseeds, making crop selection a crucial strategy for risk mitigation. Moreover, physiological traits such as salt exclusion capacity, antioxidant enzyme levels, and root-to-shoot translocation efficiency determine the degree of stress resistance in different cultivars (Rattan et al., 2022).

In sum, wastewater irrigation exerts a spectrum of effects on plant physiology—from beneficial nutrient supplementation to toxic stress, depending on water quality, soil conditions, and crop characteristics. These physiological alterations have direct implications for yield, food safety, and ecosystem services, underscoring the need for integrated monitoring, treatment, and crop management strategies in wastewater-fed systems.

Consequences for the Soil–Plant–Atmosphere Interface (SPAI)

The soil–plant–atmosphere interface (SPAI) is a highly dynamic zone where physical, chemical, and biological exchanges govern agricultural productivity and environmental interactions. Wastewater irrigation disrupts this continuum by introducing contaminants and altering energy and mass fluxes across the system. The implications extend beyond individual components—soil degradation, plant toxicity, or atmospheric emissions—to systemic changes in water cycling, greenhouse gas dynamics, and microclimatic feedbacks (Figure 1). As such, evaluating wastewater impacts at the SPAI level is critical for understanding long-term agroecosystem health and climate-related consequences.

One of the key impacts of wastewater on the SPAI is the alteration of evapotranspiration (ET) dynamics, which links plant physiology and atmospheric moisture fluxes. The salinity and ionic imbalance in wastewater reduce stomatal conductance, photosynthetic rate, and transpiration, affecting the latent heat flux from the canopy to the atmosphere (Rai et al., 2023). Salinity-induced stomatal closure, common in crops irrigated with high EC wastewater, limits plant cooling capacity and intensifies canopy temperatures, especially in arid climates. This modifies the energy partitioning between sensible and latent heat, potentially exacerbating local warming through reduced evaporative cooling (Zhao et al., 2023).

Simultaneously, soil conditions under wastewater irrigation—such as reduced porosity, surface sealing, and compaction—limit infiltration and increase runoff, altering the water balance at the land surface. These changes may reduce soil moisture storage and influence atmospheric boundary layer development, particularly in irrigated landscapes that contribute to regional climate regulation. Altered soil water content also modifies plant root water uptake patterns, further affecting transpiration efficiency and vapor exchange rates (Li et al., 2022).

Another major concern is the enhancement of greenhouse gas (GHG) emissions from wastewater-irrigated soils. Elevated nitrogen levels from municipal or industrial wastewater stimulate nitrification and denitrification, increasing nitrous oxide (N₂O) emissions—a potent GHG with a global warming potential 298 times greater than CO₂. Anaerobic microsites created by excessive organic loading or poor drainage also enhance methane (CH₄) production, especially in paddy soils or high-clay content fields (Suthar et al., 2022). The release of carbon dioxide (CO₂) from microbial respiration is also intensified by the labile carbon present in untreated effluents, contributing to atmospheric carbon loading.

Volatilization of ammonia (NH₃) is another atmospheric pathway influenced by wastewater irrigation. Ammonium-rich effluents, when applied to high-pH soils or during hot, dry weather, can lead to rapid NH₃ loss from the soil surface. These emissions contribute not only to atmospheric nitrogen loading and secondary aerosol formation but also to indirect N₂O production after redeposition (Rattan et al., 2022).

The SPAI is also disrupted by changes in plant–microbe signaling within the rhizosphere. Antibiotics, surfactants, and pharmaceuticals in wastewater interfere with quorum sensing, nodulation, and root exudate-mediated interactions essential for microbial colonization and nutrient cycling. These disruptions can reduce

nitrogen fixation, mycorrhizal colonization, and the overall stability of the soil food web, leading to cascading effects on plant water use efficiency and stress responses (Gatica & Cytryn, 2022).

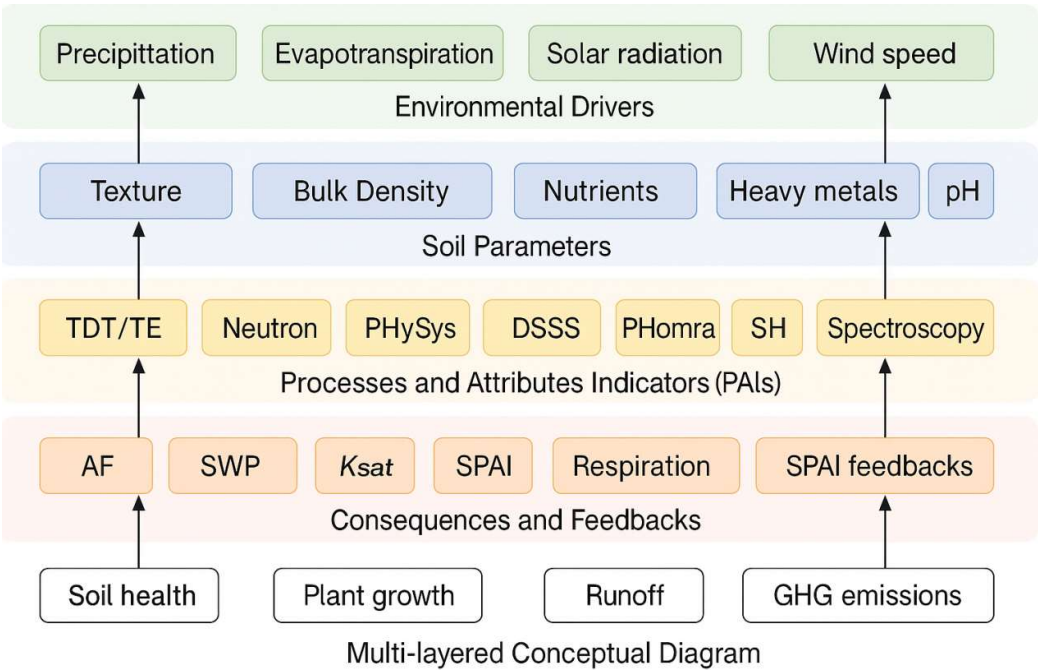


Figure 1: The framework of soil degradation, plant toxicity, or atmospheric emissions—to systemic changes in water cycling, greenhouse gas dynamics, and microclimatic feedbacks.

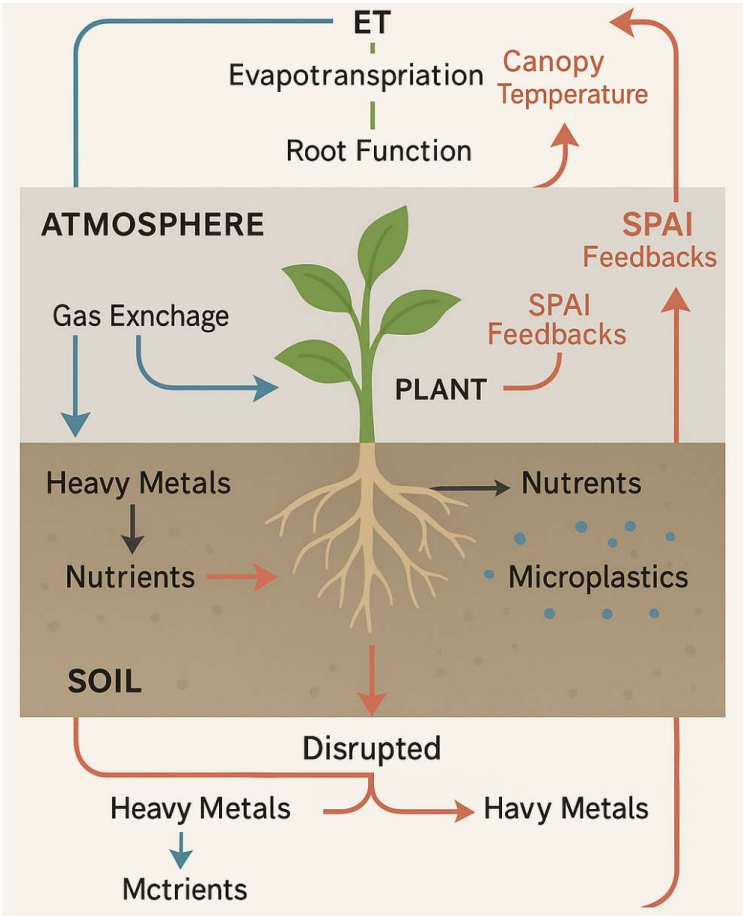


Figure 2: A successful mitigation framework combines technological treatment methods, soil and crop management practices, and institutional and monitoring tools.

Emerging contaminants, particularly microplastics and nanoplastics, further complicate SPAI dynamics. These particles interfere with capillary rise, reduce water retention, and impede gas diffusion in soil. Their hydrophobic properties promote adsorption of heavy metals and organic pollutants, creating secondary pollutant complexes that affect root physiology and soil gas exchange (Li et al., 2022). Studies suggest that microplastic-contaminated soils exhibit reduced microbial respiration and altered N₂O emission profiles due to shifts in microbial community composition.

Wastewater irrigation can also influence canopy–atmosphere interactions through changes in leaf surface properties. Contaminants such as surfactants and metal ions may accumulate on leaf cuticles, altering reflectance, wettability, and stomatal behavior. This affects radiation balance, boundary layer resistance, and transpiration rates, with downstream consequences for canopy energy exchange and microclimate modification (Bhattarai et al., 2022).

Beyond biophysical changes, the feedbacks from SPAI disturbances can reinforce land degradation and climate vulnerability. For instance, reduced plant water use efficiency combined with impaired root–soil contact can increase crop failure risk under drought, while elevated GHG emissions from wastewater-irrigated lands may compromise the climate mitigation potential of conservation agriculture (Zhang et al., 2023). These feedbacks underscore the importance of viewing wastewater reuse not just as a water management issue but as a systemic challenge to land–atmosphere interactions.

Despite these concerns, properly managed treated wastewater can support SPAI integrity. When contaminants are removed or neutralized, the additional moisture and nutrients can improve plant–atmosphere coupling by enhancing canopy development and increasing latent heat flux. In semi-arid regions, treated wastewater has been shown to enhance soil moisture buffering, increase transpiration efficiency, and maintain evapotranspiration even under heat stress conditions—thus stabilizing the local energy balance (FAO, 2023).

To sustainably integrate wastewater into irrigation systems, monitoring SPAI-related indicators—such as ET, GHG emissions, soil moisture, and microbial function—must become standard practice. Tools such as eddy covariance towers, gas flux chambers, and isotopic tracers offer precise ways to quantify SPAI impacts and guide adaptive management strategies. Ultimately, a systems-based approach is needed to ensure that wastewater reuse supports productivity, environmental quality, and atmospheric stability in tandem.

Remediation and Mitigation Approaches

To ensure the sustainability of wastewater use in agriculture, effective remediation and mitigation approaches are essential. These strategies aim to reduce or neutralize the harmful effects of contaminants on soil, plant systems, and the broader soil–plant–atmosphere interface (SPAI), while retaining the beneficial components such as water and nutrients. A successful mitigation framework combines technological treatment methods, soil and crop management practices, and institutional and monitoring tools to address both immediate toxicity and long-term ecological degradation (Figure 2).

One of the most direct and impactful strategies is the treatment of wastewater prior to irrigation. While full-scale wastewater treatment plants (WWTPs) with tertiary-level purification are ideal, they are often economically and logistically inaccessible in low-resource settings. Therefore, decentralized and low-cost treatment systems such as constructed wetlands, waste stabilization ponds, and biofilters have gained attention. Constructed wetlands mimic natural purification processes by utilizing aquatic plants (e.g., *Typha*, *Phragmites*) and microbial communities to remove pathogens, nutrients, and even heavy metals (Suthar et al., 2022). These systems are low maintenance and suitable for rural or peri-urban farms, although land requirement and seasonal efficacy may limit their scalability.

Biochar-based filtration systems are another promising innovation. Biochar, a carbon-rich product from pyrolyzed biomass, has high surface area and cation exchange capacity, allowing it to adsorb heavy metals, antibiotics, and nutrients. Studies have shown that passing wastewater through biochar-amended beds significantly reduces COD, ammonium, and Pb/Cd levels before irrigation (Rathod et al., 2023). When combined with sand or zeolite, such filters offer modular, on-farm treatment options that can be integrated into existing irrigation infrastructure.

At the soil level, amendments such as gypsum, lime, compost, and zeolites can buffer contaminant impacts. Gypsum helps displace sodium in sodic soils, improving structure and permeability. Lime neutralizes acidity and stabilizes heavy metals, reducing their bioavailability. Organic amendments enhance microbial activity, increase cation exchange capacity, and improve water retention, thereby mitigating both physical and biological stresses induced by wastewater (Rattan et al., 2022). Phytoremediation, the use of plants to extract or immobilize pollutants, is also effective in long-term wastewater management. Hyperaccumulators like *Vetiveria zizanioides* and *Brassica juncea* can be intercropped or rotated with food crops to reduce soil metal burdens.

Crop selection and diversification is a crucial biological strategy. Non-edible crops (e.g., bioenergy grasses, industrial fiber crops like hemp or kenaf) can be grown in wastewater-irrigated areas to minimize health risks while utilizing the water and nutrient content. Where food crops are prioritized, selecting cultivars with low contaminant translocation, salt tolerance, or heavy metal exclusion traits is essential. For example, certain rice and maize varieties exhibit low root-to-grain cadmium movement, making them safer for cultivation on marginal soils (Li et al., 2022).

Irrigation techniques themselves can be adjusted to reduce exposure. Subsurface drip irrigation minimizes contact between wastewater and above-ground plant parts, reducing pathogen transmission and leaf surface contamination. Additionally, intermittent irrigation or alternate wetting and drying (AWD) in rice fields has been shown to reduce both methane emissions and contaminant mobility in wastewater-fed paddies (Nguyen et al., 2022).

Robust monitoring and risk assessment frameworks are also indispensable. Regular testing of wastewater for key parameters (BOD, EC, pathogens, heavy metals), along with soil and crop tissue analysis, enables early detection of harmful trends and guides adaptive responses. Simple test kits for on-site EC, nitrate, or pathogen detection are now available and can support farmer decision-making, especially when institutional oversight is weak (FAO, 2023).

Institutional strategies—such as regulation enforcement, farmer training, and incentive structures—play a vital role in promoting responsible wastewater reuse. Government-supported wastewater reuse policies in Jordan, Israel, and Tunisia, for instance, have coupled subsidy programs for treatment infrastructure with strict irrigation guidelines based on crop type and effluent quality. In regions lacking such governance, participatory water management and community-based treatment cooperatives may provide viable alternatives (Qadir et al., 2022).

Emerging approaches also explore precision agriculture tools for wastewater optimization. Remote sensing and AI-based scheduling systems can monitor crop water stress, soil salinity, and pathogen hotspots, allowing targeted wastewater application and minimizing overexposure. Integration of Internet of Things (IoT) devices with moisture and contaminant sensors offers real-time control and feedback for smart irrigation under wastewater reuse scenarios (Ghosh et al., 2023).

Importantly, no single remediation strategy is sufficient in isolation. Integrated approaches—combining water treatment, soil amendments, crop management, and policy instruments—offer the most resilient path forward (Table 2). These strategies must be tailored to the local agroecological conditions, economic constraints, and sociocultural factors of each community. Developing context-specific wastewater management packages that balance food production, environmental protection, and public health will be central to unlocking the potential of wastewater in sustainable agriculture.

Table 2: Mitigation Options for Key Wastewater Challenges in Agriculture

Challenge	Remediation Strategy	Tool/Method	Benefits	Limitations
Heavy metal accumulation	Soil amendment	Lime, zeolite, compost	Reduces bioavailability	Site-specific efficacy
Pathogen transmission	Irrigation method	Subsurface drip	Avoids crop contact	High initial cost
Salinity/sodicity	Soil conditioner	Gypsum application	Improves structure, leaches Na ⁺	May need repeated application
GHG emissions	Field practice	AWD in rice, composting	Cuts CH ₄ and N ₂ O	Requires training
Organic contaminants	Water treatment	Constructed wetlands, biochar filters	Degrades toxins	Land or setup constraints

Conclusion

The increasing reliance on wastewater for agricultural irrigation reflects both the urgency of global water scarcity and the emerging opportunities in resource recovery and circular water management. However, the application of wastewater—particularly when untreated or poorly regulated—poses complex challenges that extend beyond soil and plant health to broader environmental and atmospheric processes. This review highlights that wastewater irrigation fundamentally alters the soil–plant–atmosphere interface (SPAI), affecting evapotranspiration dynamics, greenhouse gas emissions, soil structure, plant physiology, and microbial functioning.

While treated wastewater can provide agronomic benefits through nutrient supplementation and reliable water supply, the risks associated with heavy metals, pathogens, salinity, emerging contaminants, and systemic feedbacks require careful consideration. Impacts on soil fertility, food safety, and atmospheric exchanges underscore the necessity of managing wastewater reuse not merely as a water input, but as an ecological disturbance with multi-scalar effects.

To transition toward safe and productive wastewater reuse, future strategies must be multi-layered. Technological solutions such as decentralized treatment, biofiltration, and IoT-enabled smart irrigation offer promising tools to reduce contaminant loads and improve precision in water delivery. Complementary field-level practices—including soil amendments, phytoremediation, crop selection, and irrigation technique adaptation—can further buffer the agroecosystem against long-term degradation.

Policy and institutional frameworks are equally crucial. Comprehensive guidelines on wastewater quality thresholds, crop suitability, and health safeguards must be enforced alongside capacity-building initiatives that empower farmers to understand and mitigate wastewater-related risks. Without supportive governance, infrastructure investment, and participatory innovation, wastewater reuse will remain an ad-hoc, potentially hazardous practice rather than a sustainable solution.

Finally, there is an urgent research need to explore cumulative and long-term effects of wastewater on the SPAI under real-world field conditions. Integration of SPAI dynamics into climate-smart agriculture models, food safety surveillance, and carbon accounting systems will help evaluate trade-offs and synergies. By framing wastewater

reuse within systems ecology, researchers and practitioners can develop context-specific solutions that enhance resilience, productivity, and sustainability across interconnected environmental interfaces.

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