

## PHYTOREMEDIATION OF GREYWATER USING PLANTS: *BRASSICA JUNCEA* AND *HELIANTHUS ANNUS*

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### Abstract

Freshwater constitutes approximately 2.5% of the total water on earth, of which 70% is stored in glaciers and polar ice caps, while 30% exists in liquid form. Of this, < 1% is directly accessible for human consumption. The increasing scarcity of freshwater resources underscores the need for sustainable and efficient greywater treatment solutions. Therefore, this review aims to explore integrated biotechnological strategies using *Brassica juncea* (Indian mustard) and *Helianthus annuus* (sunflower) for effective greywater remediation. These plant species exhibit significant phytoremediation potential owing to their rapid growth, high biomass production, and ability to accumulate and detoxify diverse contaminants, including heavy metals, organic pollutants, and nutrients. The mechanisms underlying pollutant uptake, translocation, and detoxification were discussed in detail, alongside their physiological and molecular adaptations to greywater-induced stress. Additionally, the role of plant-associated rhizospheric interactions in enhancing treatment efficiency was highlighted. This review explores the challenges and potential of scaling plant-based biotechnological systems for cost-effective, eco-friendly greywater reuse.

**Key words:** Greywater treatment; Phytoremediation; *Brassica juncea*; *Helianthus annuus*; Sustainable wastewater management; Bioremediation; Water reuse

### Introduction

Greywater reuse has emerged as a crucial strategy for mitigating global water scarcity, which is intensified by rapid urbanization, industrialization, and climate change (Pinto *et al.*, 2021). Greywater generation from domestic activities—such as laundry, bathing, and kitchen use—accounts for a significant proportion of total wastewater. Although less contaminated than blackwater, greywater contains significant amounts of organic matter, nutrients, pathogens, and trace amounts of heavy metals, which can pose environmental and health risks if not properly managed (Awasthi *et al.*, 2024). Conventional greywater treatment methods, including physicochemical and biological processes, often face challenges, including high operational costs, excessive energy consumption, and the generation of secondary pollutants. These challenges highlight the need for sustainable, cost-effective, and eco-friendly alternatives, with phytoremediation-based biotechnological strategies emerging as a promising solution (Mmonwuba *et al.*, 2024; Sharma *et al.*, 2025). The use of plants in greywater treatment offers an innovative approach, harnessing their natural ability to accumulate, degrade, and detoxify diverse pollutants while supporting ecosystem restoration and enhancing aesthetics.

Greywater has a heterogeneous composition with high concentrations of surfactants, organic compounds, nutrients, and varying levels of heavy metals, posing significant treatment challenges (Kepoğlu *et al.*, 2018). These contaminants originate from diverse domestic activities and industrial effluents, leading to fluctuating pH levels, high chemical oxygen demand (COD) and biological oxygen

demand (BOD), alongside the presence of emerging pollutants such as microplastics and pharmaceuticals (Amaris *et al.*, 2021; Filali *et al.*, 2022). Traditional treatment methods, including sedimentation, filtration, and activated sludge processes, often struggle to manage this variability, producing inconsistent treatment outcomes and generating chemically laden sludge that requires additional management. Furthermore, the high operational and maintenance costs of advanced treatment systems such as membrane filtration and reverse osmosis limit their applicability in decentralized and resource-limited settings (Kabiri *et al.*, 2021). In this context, phytoremediation provides a viable and sustainable alternative, leveraging natural plant processes to treat greywater in an environmentally friendly and cost-effective manner. Phytoremediation exploits the ability of certain plant species to absorb, sequester, and detoxify pollutants through complex physiological and biochemical mechanisms. This approach reduces pollutant concentrations while simultaneously supporting biomass production and enhancing the landscape (Abed *et al.*, 2019).

Biotechnological enhancement of phytoremediation systems can significantly improve the efficiency and resilience of greywater treatment processes. Advances in genetic engineering and molecular biology have facilitated new approaches to enhance the pollutant tolerance and accumulation capacities of phytoremediation species (Ozyigit *et al.*, 2021; Li *et al.*, 2022). Overexpression of genes related to metal transporter proteins, antioxidant defense mechanisms, and stress-responsive transcription factors may significantly improve the phytoremediation potential of the plants (Eapen & D'souza, 2005). Additionally, integrating plants with

competent microbial flora (Dilawar *et al.*, 2024), including plant growth-promoting rhizobacteria (PGPR), enhances nutrient uptake efficiency and stress resilience, thereby contributing to more effective greywater remediation. Recently, Khan *et al.*, (2018) report the significant role of PGPR in improving phytoremediation efficiency and enhancing drought tolerance in *H. annuus* plants. Their research shows that PGPR inoculation increases phytoremediation of heavy metals and enhances the accumulation of essential micronutrients. Particularly, the co-inoculation of two PGPR strains (*Planomicrobium chinense* and *Bacillus cereus*) along with salicylic acid (SA) is effective in promoting plant growth and mitigating heavy metal toxicity. Moreover, PGPR inoculation stimulated the production of auxins (indole-3-acetic acid, IAA) and gibberellins, which are crucial for enhancing plant stress tolerance (Khan *et al.*, 2018). Raj *et al.*, (2020) report that *B. juncea* tolerates high levels of mercury (Hg) contamination and exhibits significant potential for phytostabilizing of Hg when grown in soil containing 100 mg/kg of Hg, without noticeable adverse effects on plant growth (Raj *et al.*, 2020). Furthermore, Ashraf *et al.*, (2024) report that the combined application of PGPR (*Pseudomonas aeruginosa*) and acidified organic amendment improves the antioxidative defense mechanism of *B. juncea*, suggesting its effectiveness for phytoremediation of Cd-contaminated soil (Ashraf *et al.*, 2024).

Engineered constructed wetlands using these plant species offer scalable solutions for decentralized wastewater treatment, providing pollutant removal alongside ecosystem services such as habitat creation, carbon sequestration, and beneficial microbial interactions. Plants within these systems support microbial communities by supplying surface for colonization and facilitating nutrient cycling, thereby enhancing contaminant breakdown efficiency. These biotechnological strategies demonstrate significant promise in addressing wastewater management challenges in urban and rural settings. Despite these advances, several critical challenges impede the widespread adoption of phytoremediation-based greywater treatment systems. The variability in greywater composition complicates the standardization of treatment protocols and ensuring consistent pollutant removal efficiencies (Vuppalladadiyam *et al.*, 2019; He *et al.*, 2022). This review explores the potential of *B. juncea* and *H. annuus* for greywater treatment, emphasizing pollutant removal, biotechnological enhancements, and integration into sustainable systems, while addressing challenges and future research for eco-friendly, cost-effective solutions.

### Greywater Treatment via Phytoremediation:

Greywater often contains various contaminants, including organic matter such as detergents, oils, and food waste, contributing to its high COD and BOD (Budeli & Sibali, 2025; Faggiano *et al.*, 2025). Greywater pH ranges from slightly acidic to alkaline, affecting the treatment efficiency of certain processes such as microbial degradation (Mohan *et al.*, 2024). Heavy metals in greywater, originating from cleaning agents and personal care products, pose long-term ecological risks if not effectively removed (Eriksson & Donner, 2009). Nutrients, particularly nitrogen and phosphorus, can promote eutrophication in receiving waters if greywater is inadequately treated (Mekonnen *et al.*, 2016). Additionally, greywater contains various pathogens that

pose public health risks, particularly when used for irrigation or discharged into natural waters untreated (Nagarkar *et al.*, 2021). Surfactants from laundry and cleaning products further complicate treatment by hindering biological degradation processes.

Given these limitations, sustainable and cost-effective alternatives are crucial for the safe reuse of greywater. Phytoremediation—the use of plants to remove, stabilize, or degrade environmental pollutants—offers a promising nature-based solution (Patnaik & Abbasi, 2020). Certain plant species, including *Brassica juncea* and *Helianthus annuus*, show strong potential for mitigating greywater pollutants due to high biomass production, environmental stress tolerance, and efficient pollutant uptake mechanisms (Singh *et al.*, 2024). These plants use phytoextraction, phytodegradation, and phytostabilization to remove organic and inorganic contaminants while supporting ecosystem restoration (Fig. 1).

Although phytoremediation has inherent advantages, plant-based treatment efficiency systems can be enhanced through biotechnological interventions. Genetic modification targeting pollutant transporters, antioxidant defense mechanisms, and stress-responsive pathways can increase plant tolerance and remediation capacity. Additionally, their interaction with plant growth-promoting rhizobacteria improves nutrient uptake and stress resistance, further enhancing pollutant removal efficiency (Singh *et al.*, 2017; Saha *et al.*, 2021). Engineered constructed wetlands incorporating these advancements offer scalable and sustainable solutions for greywater treatment, delivering contaminant removal and additional environmental benefits including carbon sequestration and biodiversity support (Siriwardhana *et al.*, 2023; Maiga *et al.*, 2024). However, significant challenges continue to limit the widespread adoption of these technologies. Variability in greywater composition complicates treatment system standardization, and the long-term sustainability and resilience of plant-based solutions under continuous pollutant exposure require further validation. Additionally, the management of pollutant-laden biomass from phytoremediation processes poses environmental concerns, requiring safe disposal or valorization pathways. Economic feasibility studies and supportive policy frameworks are lacking, hindering large-scale implementation and public acceptance of these systems.

**Phytoremediation Potential of *B. juncea* and *H. annuus*:** *B. juncea* is a robust phytoremediation plant that accumulates diverse pollutants while maintaining relatively high biomass. The effectiveness of *B. juncea* can be further improved through soil amendments and growth enhancers (Chen *et al.*, 2020; Qadir *et al.*, 2024). Similarly, *Helianthus annuus* (common sunflower) is a robust plant with an extensive fibrous root system and significant above-ground biomass, enabling contaminant absorption in large quantities and translocation of pollutants from roots to shoots. Sunflower (*H. annuus*) is a robust and versatile phytoremediator, particularly effective for heavy metals including Cd, Pb, and Zn. The effectiveness of this species can be enhanced by selecting suitable varieties, using beneficial microbes, and applying soil amendments (Alaboudi *et al.*, 2018; Mathur *et al.*, 2022). Both species tolerate abiotic stresses, including drought, salinity, and heavy metal exposure, making them ideal for greywater

treatment under variable environmental conditions. Table 1 shows a comparison of the botanical and physiological traits of *B. juncea* and *H. annuus*, plant species with significant phytoremediation potential.

*B. juncea* has a short growth cycle and a well-developed taproot system, enabling rapid biomass production and efficient uptake of heavy metals, including lead, cadmium, and zinc. This makes it highly suitable for contaminated sites requiring rapid remediation (Chen *et al.*, 2023). *B. juncea* is a fast-growing and effective plant for the phytoremediation of soils contaminated with heavy metals, including Pb, Cd, and Zn. The performance of *B. juncea* can be enhanced with microbial inoculants, chelators, and organic amendments, making it a practical option for rapid and efficient site remediation (Jeyasundar *et al.*, 2021). In contrast, *H. annuus* has a longer growth cycle but a deep fibrous root system that efficiently absorbs a broad spectrum of nutrients and heavy metals. Furthermore, its larger biomass yield and tolerance to environmental stresses make it ideal for long-term phytoremediation projects, particularly for nutrient recovery and organic pollutant degradation. However, the high water requirements in *H. annuus* and potential nutrient depletion in the soil over time pose challenges in resource-limited settings (Chauhan & Mathur, 2020; Chauhan *et al.*, 2020). While both plants exhibit phytoremediation strength, optimizing their effectiveness requires understanding their unique traits and the environmental conditions of the treatment site.

Physiologically, these plants have well-regulated transpiration rates and efficient photosynthetic machinery that sustain their growth even under pollutant-induced stress conditions (Singh & Fulekar, 2012; Marques *et al.*, 2013). Specialized transport proteins in root cell membranes facilitate the active uptake of heavy metals and nutrients from greywater. Additionally, their ability to secrete root exudates, including organic acids and chelating agents, enhances pollutant bioavailability and absorption efficiency (Marques *et al.*, 2013; Paulo *et al.*, 2023). These exudates also modulate the rhizospheric microbial community, assisting in organic pollutant degradation and supporting overall phytoremediation efficiency. Leaves and stems anatomical features, including high stomatal density and thick cuticles, facilitate the sequestration and storage of absorbed contaminants, thereby reducing their mobility and toxicity within the plant tissues (Chauhan & Mathur, 2020; Mathur *et al.*, 2022).

In *B. juncea* and *H. annuus*, pollutant uptake occurs through passive and active transport regulated by specific physiological and biochemical pathways. After root absorption, pollutants such as heavy metals are sequestered in vacuoles or bound to metal-chelating compounds such as phytochelatins and metallothioneins to prevent cellular toxicity (Lee *et al.*, 2002; Malecka *et al.*, 2021). Organic contaminants, including detergents and surfactants commonly found in greywater, are degraded enzymatically by oxidoreductases, peroxidases, and dehydrogenases (Thakur *et al.*, 2019; Zhang *et al.*, 2023). These enzymes break down complex organic molecules into less harmful compounds that plants can metabolize or further degrade into harmless end products. When pollutants cannot be metabolized, they are compartmentalized within plant tissues, effectively isolating them from vital metabolic processes (Fig. 2).

Comparative performance analyses reveal that *B. juncea* and *H. annuus* offer substantial benefits in greywater treatment, though their effectiveness varies with certain contaminants and environmental conditions. *B. juncea* exhibits superior performance in heavy metal uptake—particularly for lead, cadmium, and chromium—due to its strong metal-binding capacity and high translocation efficiency (Salinitro *et al.*, 2021; Peng *et al.*, 2024). Its short life cycle and rapid biomass growth make it ideal for periodic harvesting and pollutant removal. Conversely, *H. annuus* demonstrates exceptional capability in nutrient recovery, effectively reducing nitrogen and phosphorus levels in greywater (Jhonson *et al.*, 2022; Ramzan *et al.*, 2024). Its deep root enhances nutrient absorption, and high transpiration rate facilitates water loss, promoting the concentration and removal of dissolved pollutants. Figure 3 depicts a detailed overview of plant uptake, translocation, accumulation, and detoxification of pollutants. Pollutants are first absorbed through the roots, enter the vascular system of the plant, and are transported to the shoots (Fig. 3). In the shoots, pollutants are sequestered in vacuoles, isolating them from other cellular components. Detoxification mechanisms include chelation, in which metal-binding proteins or molecules bind pollutants to reduce toxicity, and antioxidant systems that neutralize pollutant-induced oxidative stress (Bartha *et al.*, 2010; Yang *et al.*, 2023). Additionally, the figure illustrates pollutant accumulation in various plant tissues, which serves as a mechanism to concentrate and isolate toxic substances. Ultimately, these processes work together to reduce plant toxicity, enabling survival and adaptation in contaminated environments.

**Table 1. Comparative botanical and physiological traits of *B. juncea* and *H. annuus*.**

| Trait              | <i>B. juncea</i>             | <i>H. annuus</i>                    | Advantages of Phytoremediation                                      |
|--------------------|------------------------------|-------------------------------------|---------------------------------------------------------------------|
| Growth cycle       | Short (90–120 days)          | Moderate (120–150 days)             | Faster biomass production for periodic harvesting                   |
| Root system        | Taproot                      | Fibrous, deep root system           | Efficient nutrient and pollutant uptake from deeper soil layers     |
| Biomass yield      | High                         | Very high                           | High biomass for enhanced pollutant uptake                          |
| Stress tolerance   | Moderate-high                | High                                | Tolerates moderate pollutant load, useful for specific contaminants |
| Heavy metal uptake | Excellent for Pb, Cd, and Zn | Moderate for Cd and Pb              | Can accumulate and detoxify a wide range of metals                  |
| Water requirements | Moderate                     | High                                | Needs moderate irrigation, adaptable to varying water availability  |
| Nutrient uptake    | Moderate (N, P, K)           | Excellent (N, P, K, micronutrients) | Can enhance nutrient cycling and soil quality                       |

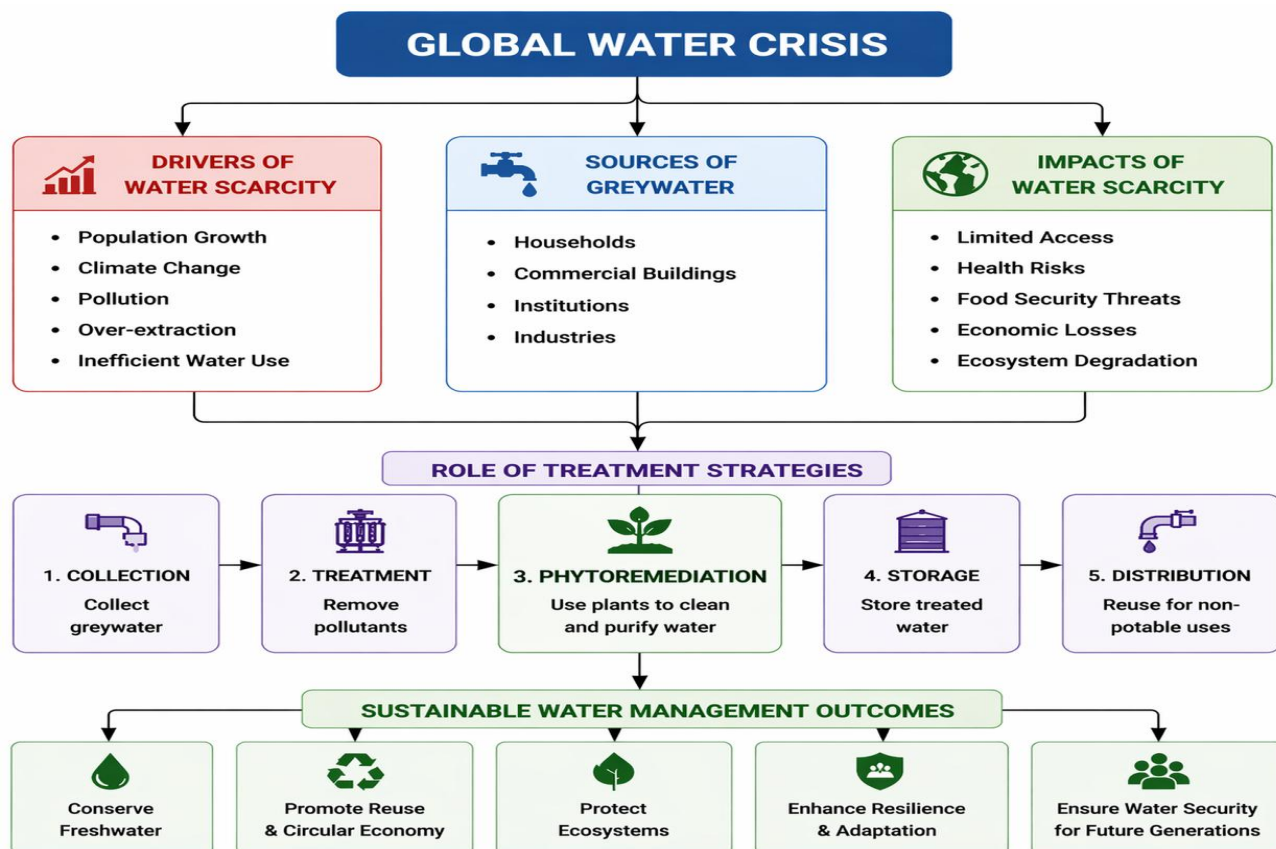


Fig. 1. Illustrates the drivers of water scarcity, sources of greywater generation, and the role of treatment strategies in sustainable water management.

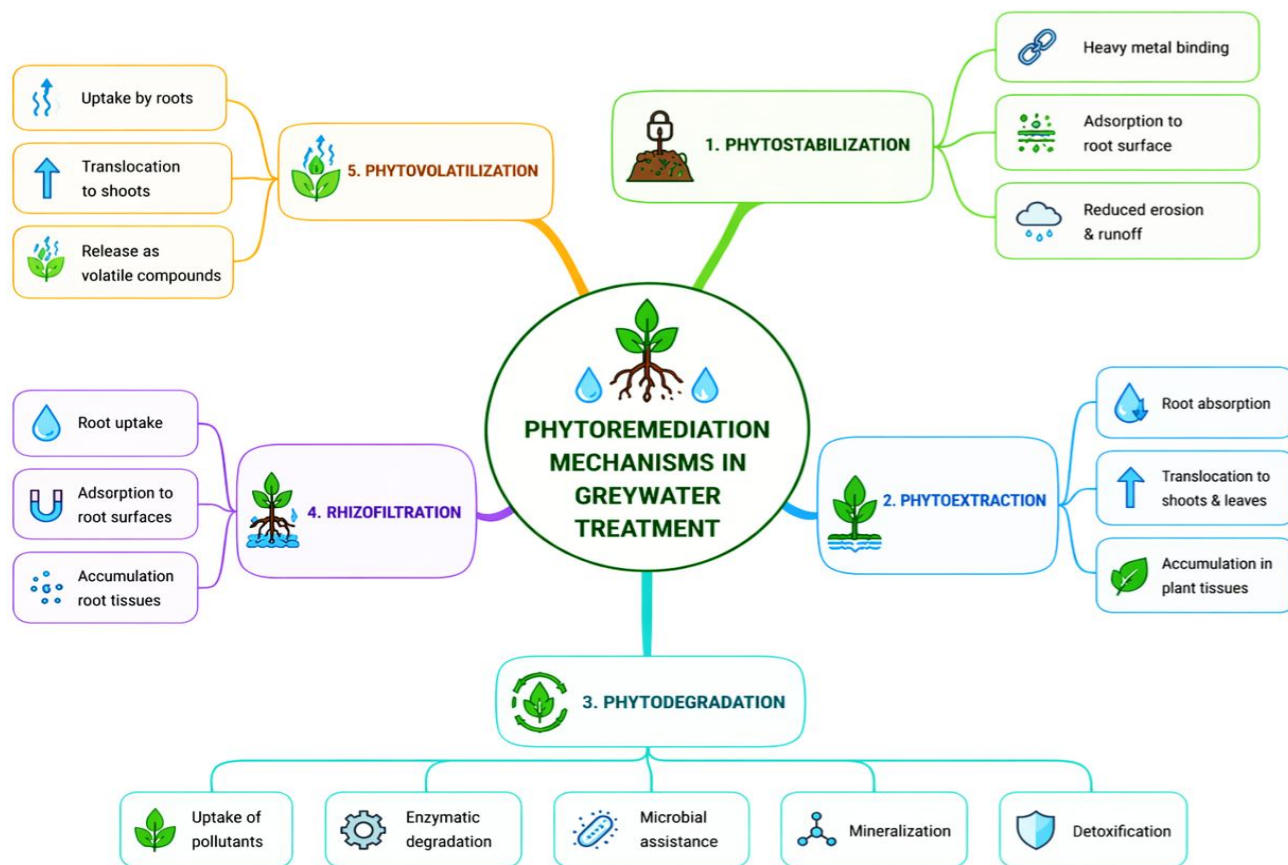


Fig. 2. Demonstrates key phytoremediation strategies such as phytostabilization, phytoextraction, phytodegradation, rhizofiltration, and phytovolatilization. These mechanisms support sustainable greywater treatment.

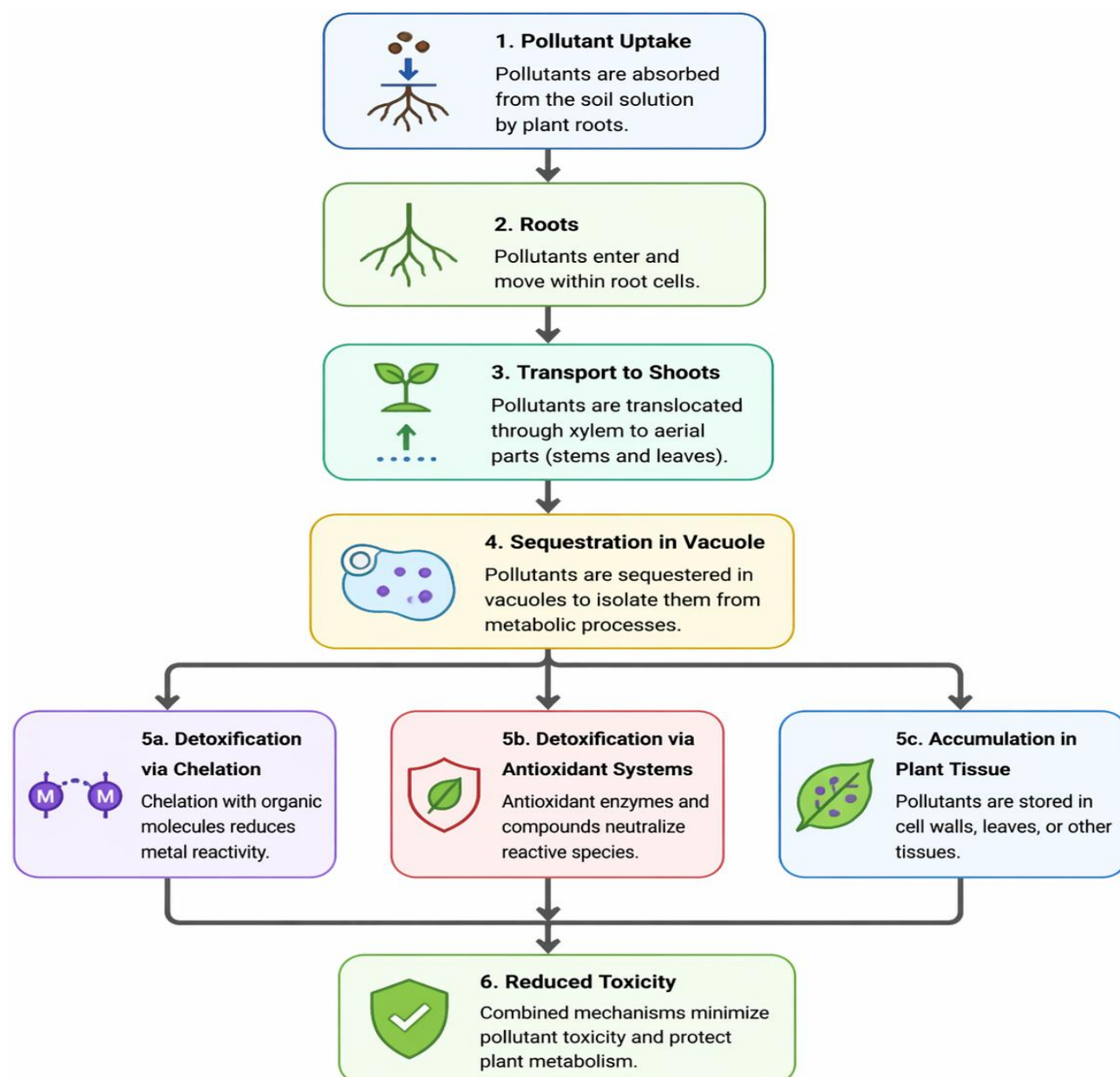


Fig. 3. Flowchart illustrating the pollutant uptake, translocation, accumulation, and detoxification mechanisms in plants. The figure depicts the pathway from root uptake of pollutants to shoot transport, vacuolar sequestration, and subsequent detoxification via chelation and antioxidant systems. It also includes pollutant accumulation in plant tissues, which helps reduce toxicity.

In practical greywater treatment applications, species choice often depends on specific remediation goals. *B. juncea* is generally preferred for removing heavy metals and toxic elements. In contrast, *H. annuus* outperforms in nutrient recovery and organic pollutant degradation (Pietrini *et al.*, 2021; Ramzan *et al.*, 2022). Integrating both species in a single constructed wetland or treatment system can maximize the overall efficiency by targeting a wider range of pollutants. This complementary use enhances pollutant removal and supports system resilience and ecological diversity. These findings indicate the need to select appropriate phytoremediation species based on the contaminant profile of greywater and the site-specific conditions.

**Biotechnological enhancements for improved greywater remediation:** Biotechnological interventions have enhanced phytoremediation potential for greywater treatment by improving pollutant tolerance, uptake

efficiency, and metabolic degradation capabilities of plants (Hellal *et al.*, 2024; Zaman *et al.*, 2024). Traditional phytoremediation relies on the natural abilities of plants to absorb and detoxify contaminants; however, environmental stressors and certain pollutant toxicity often limit these capacities. Targeted genetic modifications, enabled by genetic engineering and molecular biology, offer powerful tools to overcome these limitations that strengthen the physiological resilience and pollutant processing efficiency of phytoremediation species (Yadav *et al.*, 2010; Kumar *et al.*, 2023). These enhancements—overexpressing metal transporter proteins, detoxification enzymes, and stress-responsive regulatory genes—enable plants to tolerate higher contaminant loads while maintaining robust growth and biomass production (Fig. 4). These advancements ensure consistent and effective greywater remediation, particularly in environments with complex and variable pollutant compositions.

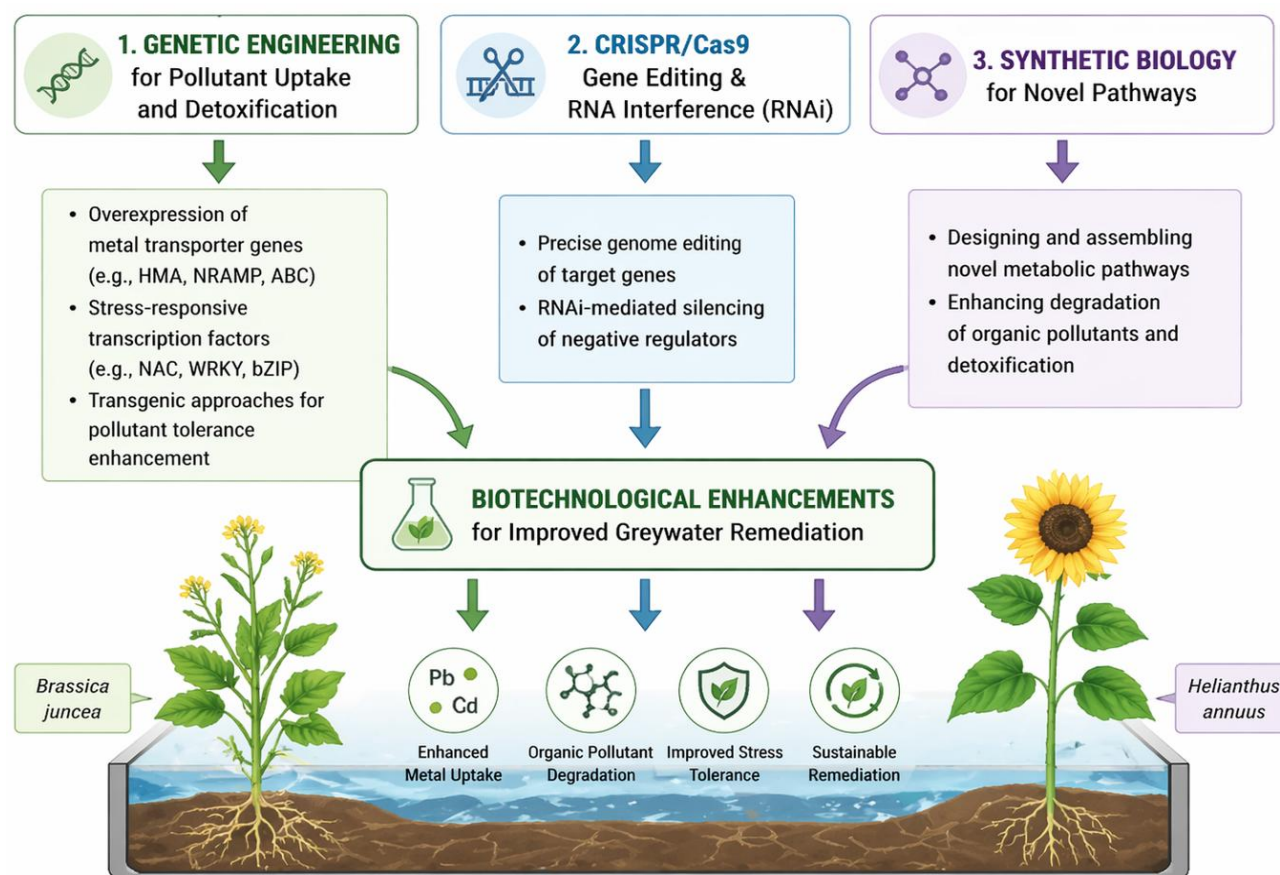


Fig. 4. Biotechnological approaches for enhancing Greywater Remediation using *B. juncea* and *H. annuus*.

At the molecular level, various strategies have been explored to enhance the phytoremediation capacity of plants such as *Brassica juncea* and *Helianthus annuus*. One common strategy is overexpressing genes encoding for metal transporters, including the ZIP (Zinc-regulated transporter/Iron-regulated transporter-like Protein) and NRAMP (Natural Resistance-Associated Macrophage Protein) families, facilitating heavy metal uptake and translocation from the rhizosphere to shoots (Luo *et al.*, 2016; Shourie *et al.*, 2024). Additionally, introducing genes responsible for the synthesis of metal-chelating peptides—phytochelatins and metallothioneins—enhances the sequestration and detoxification of toxic metals within plant cells, mitigating their harmful effects on vital physiological processes (Pilon-Smits, 2005; Shourie *et al.*, 2024). For organic pollutant degradation, introducing genes encoding for enzymes such as laccases, peroxidases, and cytochrome P450 monooxygenases enhances the breakdown of complex organic compounds, including surfactants and pharmaceutical residues frequently present in greywater (Aryal, 2024). These genetic modifications enable plants to effectively metabolize and neutralize contaminants that would otherwise persist in the environment (Hasan *et al.*, 2019).

Beyond genetic modifications, advances in transcriptomics, proteomics, and metabolomics have provided valuable insights into the regulatory networks controlling plant responses to greywater pollutants (Chathangad *et al.*, 2025). Understanding these molecular pathways has allowed researchers to identify key transcription factors, including members of the WRKY, MYB, and NAC families that regulate the expression of stress-responsive genes involved in

antioxidant defense, osmotic adjustment, and pollutant detoxification (Erpen *et al.*, 2018; Li *et al.*, 2024). Manipulating these transcription factors via transgenic approaches or gene-editing tools such as CRISPR/Cas9 can significantly enhance the overall phytoremediation efficiency of target species (Liu *et al.*, 2024). Moreover, identifying microRNAs involved in stress response regulation offers an additional layer of control for fine-tuning gene expression under pollutant-induced stress (Fu *et al.*, 2019). These molecular strategies enhance phytoremediation plant resilience and support the development of customized treatment systems for specific greywater contaminant profiles (Han *et al.*, 2016; Hauque *et al.*, 2016).

In addition to plant-based genetic enhancements, microbial interactions play a key role in enhancing greywater remediation efficiency (Behera, 2013). PGPR have been extensively studied for their ability to enhance plant growth, nutrient uptake, and stress tolerance in contaminated environments. These beneficial microbes colonize the rhizosphere and secrete bioactive compounds—phytohormones (auxins, gibberellins, and cytokinins), siderophores, and organic acids—that enhance nutrient availability and support plant physiology (Ma *et al.*, 2016). PGPR also degrade organic pollutants by producing extracellular enzymes that break down complex organic molecules, thereby reducing pollutant load before reaching plant roots. The synergy between plants and rhizospheric microbes enhances contaminant removal and promotes healthier root development, increasing the overall efficacy of phytoremediation systems (Xun *et al.*, 2015). *P. fluorescens* and *B. subtilis* are among the most

widely studied PGPR for their ability to enhance plant growth and tolerance to pollutants (Ng *et al.*, 2022; Jaffar *et al.*, 2023). These bacteria release siderophores that chelate heavy metals, increasing their bioavailability to plants, and produce growth-promoting hormones such as IAA (Ali *et al.*, 2018; Saranraj *et al.*, 2022; Kalleku *et al.*, 2024). Other PGPR species, including *Rhizobium* spp. and *Azotobacter chroococcum* are primarily known for their nitrogen-fixing capabilities, improving nutrient availability for plants, especially in nitrogen-deficient soils (Aasfar *et al.*, 2021). These microbial interactions facilitate nutrient uptake and degrade organic pollutants, such as petroleum hydrocarbons and pesticides (Sharma *et al.*, 2023a). Additionally, *Trichoderma harzianum* enhances organic pollutant breakdown through mycoparasitism while *Enterobacter cloacae* promotes plant growth by solubilizing phosphate and producing IAA (Rajani *et al.*, 2021; Kumar & Prasad, 2025). Together, these PGPR species significantly enhance phytoremediation system efficiency by supporting healthier plant growth, increasing pollutant uptake, and aiding toxic substance degradation. This plant-PGPR synergy offers significant potential for sustainable remediation of contaminated environments, making it a valuable tool in greywater treatment and other bioremediation efforts.

Moreover, integrating engineered constructed wetlands with biotechnologically-enhanced plant species offers a scalable, practical solution for decentralized greywater treatment (Sha *et al.*, 2024). Constructed wetlands are designed to replicate natural wetland ecosystems, offering a controlled environment for pollutant removal through a combination of physical, chemical, and biological processes (Shukla *et al.*, 2022). Incorporating genetically improved plants such as *B. juncea* and *H. annuus* into these systems can significantly enhance treatment efficiency, particularly for greywater rich in nutrients, heavy metals, and organic pollutants. Engineered wetlands can be further optimized through design modifications that improve hydraulic retention times, flow patterns, and aeration, ensuring better pollutant-root contact (Rahman *et al.*, 2020). Additionally, supporting microbial consortia within the wetland substrate enhances organic contaminant degradation, providing a holistic and sustainable treatment solution.

Integrating treatment systems that combine phytoremediation with complementary technologies such as biofilters, sedimentation tanks, and membrane filtration units can enhance greywater management effectiveness (Yoonus & Al-Ghamdi, 2020; Hassan *et al.*, 2024). These hybrid systems leverage the strengths of each treatment method, using physical processes that remove suspended solids and contaminants with biological and phytoremediation components that treat dissolved pollutants. Such multi-stage treatment designs are particularly effective for treating the complex and variable nature of greywater produced from diverse domestic and industrial sources. The modularity of these systems enables flexible scaling to match community needs and available resources (Boano *et al.*, 2019). With increasing interest in sustainable water management, the development and implementation of integrated, biotechnologically enhanced greywater treatment systems will be key to advancing water reuse, reducing environmental pollution, and supporting global efforts toward achieving water security.

**Challenges and Future Perspectives:** Despite their significant promise, phytoremediation-based greywater treatment systems face several ecological and practical limitations that hinder their large-scale application and long-term sustainability. A major ecological concern is the potential for pollutant accumulation in plant tissues, which may cause secondary environmental contamination if the harvested biomass is not properly managed (Simonich & Hites, 1995; Ismael *et al.*, 2019). Plants used in phytoremediation absorb heavy metals and other toxic compounds, requiring safe disposal or reuse strategies to prevent their reintroduction into the environment. Additionally, phytoremediation efficiency depends heavily on environmental factors—including temperature, light availability, soil or substrate composition, and seasonal variations—which can cause inconsistent treatment performance. In cold or arid regions, reduced plant growth and pollutant uptake limit the year-round effectiveness of these systems (Nedjimi, 2021; Sharma *et al.*, 2023b). These ecological constraints must be carefully considered when designing and implementing greywater treatment solutions across diverse climatic and geographic regions.

Another key limitation is the absence of standardized protocols and design guidelines for phytoremediation-based greywater treatment systems. Differences in greywater composition across domestic, commercial, and industrial sources complicate the selection of suitable plant species and system designs. Without standardized guidelines for contaminant load thresholds, hydraulic retention times, and optimal plant densities, system performance remains site-specific and difficult to replicate at larger scales (Irawanto, 2021; Kulandaiswamy & Nithyanandam, 2021). This uncertainty deters policymakers and stakeholders from adopting phytoremediation solutions as a mainstream wastewater management strategy. Addressing these challenges will require the development of adaptable and modular treatment designs that manage fluctuating pollutant loads and site-specific conditions without reducing treatment efficiency.

Integrating phytoremediation into circular economy models and wastewater reuse policies offers a valuable opportunity to enhance the sustainability and economic viability of greywater treatment systems. Circular economy principles emphasize resource recovery, waste minimization, and the creation of closed-loop systems that reduce environmental impact while creating economic value (Rezania *et al.*, 2015; Mandal *et al.*, 2024). In this context, biomass harvested from phytoremediation systems can be converted into valuable by-products such as bioenergy, compost, biochar, or green fertilizers, turning waste into a resource rather than a disposal problem. For example, nutrient-rich biomass can be processed into soil amendments, while nontoxic plant material can be used for biofuel production (Rai & Nongtri, 2024). However, successful integration requires safe, efficient biomass utilization pathways that prevent the release of accumulated pollutants from re-entering the environment.

Wastewater reuse policies are vital for promoting phytoremediation in greywater management. Governments and regulatory agencies must establish clear guidelines and incentives for safely reusing treated greywater, particularly in non-potable applications such as landscape irrigation, industrial processes, and toilet flushing (Waqkene *et al.*,

2023; Azabo *et al.*, 2024). Integrating phytoremediation into existing wastewater treatment frameworks helps meet regulatory standards for water quality while reducing freshwater use. Policy tools such as subsidies for decentralized treatment systems, tax incentives for green infrastructure, and mandatory water reuse regulations can promote the implementation of plant-based treatment technologies (Sulaiman *et al.*, 2025). Collaboration among scientists, industry stakeholders, and policymakers is vital for developing holistic strategies that balance environmental, economic, and social goals in promoting sustainable greywater management.

Despite significant advancements, key research gaps must be addressed to fully realize the potential of phytoremediation-based greywater treatment systems. Long-term studies on system resilience and performance under continuous pollutant exposure are lacking, hindering predictions of effectiveness over time. Research is needed to explore the molecular and physiological mechanisms underlying plant tolerance to complex greywater pollutants, supporting the development of more resilient plant varieties through genetic engineering and molecular breeding (Khajvand *et al.*, 2022). Furthermore, the understanding of the plant-microbe synergistic interactions in greywater environments is limited, but harnessing these synergies could enhance treatment efficiency by boosting microbial degradation of organic contaminants. Future research should focus on developing standardized methodologies for system design, monitoring, and performance evaluation to ensure consistent, replicable outcomes across diverse environments. Investigating safe and cost-effective pathways for managing and valorization pollutant-laden biomass is a key priority to minimize secondary environmental influence. Additionally, interdisciplinary studies integrating phytoremediation with advanced treatment technologies, such as membrane filtration and bioelectrochemical systems, could yield hybrid treatment solutions that combine the advantages of natural and engineered processes. Addressing these research gaps will enable scalable, cost-effective, and environmentally sustainable greywater treatment solutions that strengthen water security and environmental conservation globally.

## Conclusion

Exploring phytoremediation-based strategies for greywater treatment highlights their significant potential as sustainable, cost-effective, and eco-friendly alternatives to conventional treatment methods. *B. juncea* and *H. annuus*, possess physiological and biochemical traits that enable them to absorb, transport, and detoxify a wide range of pollutants, including heavy metals, organic compounds, and emerging contaminants. Their high biomass production, tolerance to environmental stress, and adaptability to diverse greywater compositions make them ideal for decentralized treatment systems. Progresses in biotechnology, such as genetic enhancements and plant growth-promoting rhizobacteria, have significantly improved the efficiency and resilience of phytoremediation for pollutant removal. Engineered constructed wetlands and integrated treatment systems offer practical solutions for greywater management at household and community levels, promoting water conservation and environmental restoration. However, challenges like variability in greywater composition, limited plant pollutant tolerance, and biomass management must be

addressed for long-term success. The lack of standardized treatment protocols, economic feasibility analyses, and performance assessments limits widespread adoption. Future efforts should focus on hybrid treatment systems combining phytoremediation with advanced technologies, the development of genetically enhanced plants, and exploring biomass utilization for bioenergy and soil amendments. Addressing these research gaps and strengthening policies will help integrate phytoremediation into circular economy models, enhancing its potential to improve global water security.

## Declaration

**Author's Contributions:** Conceptualization, writing—original draft preparation, resources, software, validation, visualization, S.A., and F.H.A.; writing—review and editing, F.H.A. and S.A.; supervision, S.A., and F.H.A., All authors have read and agreed to the published version of the manuscript.

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