6 Prospect of Using Genetically Modified Plants in Constructed Wetlands for Wastewater Treatment

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Abstract

Constructed wetlands (CWs) are built to work like natural wetlands. They can remove pollutants from wastewater through physical, chemical, and biological processes. Commonly occuring wetland plants often have limited ability to take up pollutants, especially heavy metals. This is because, they do not have the advanced mechanisms found in transgenic plants. Conventional plants also find it difficult to break down hazardous organic contaminants, making them less effective against complex industrial pollutants and persistent substances. Genetically modified macrophytes, however, can be enhanced with genes that improve capacity to uptake metals, tolerate stress, and to break down pollutants. These improvements enable better contaminant removal, even under tough conditions. They also widen the range of pollutants that can be treated, all while keeping the wetland's structure intact. This paper reviews currently ongoing researches on using genetically modified (GM) plants in constructed wetlands, drawing from sources like ScienceDirect, ResearchGate, and Elsevier, and using keywords such as 'genetically modified plants', 'constructed wetlands' and 'wastewater treatment.' The review also includes official documents from India and other countries. It prominently shows the proven and likely benefits in treatment efficiency, examines ecological and biosafety risks of releasing transgenic macrophytes, and points out knowledge gaps and future research priorities.

Keywords

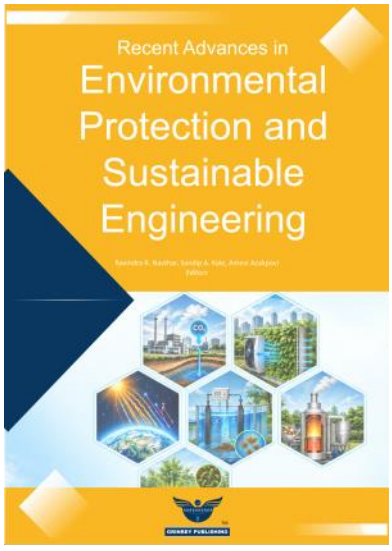
Constructed wetlands; genetically modified plants; xenobiotic degradation; pollutant removal.

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1. Introduction

The term ‘Constructed wetlands’ denote engineered treatment systems that imitate the structure and function of natural wetlands for the purpose of removing contaminants from wastewater in a cost-effective and environmentally sustainable manner. These constructed wetlands depend on the overall action of plants, microorganisms, and substrates to remove pollutants by utilising physical, chemical, and biological processes. Constructed wetlands utilise some important pollutant removal mechanisms, which are as follows: sedimentation and filtration of suspended solids; microbial degradation and transformation of organic matter and nutrients; adsorption and precipitation of contaminants onto substrates; and plant uptake and storage of nutrients and selected pollutants. These processes, when combined, help the constructed wetlands to treat municipal, industrial, and agricultural wastewater while delivering additional ecosystem services, such as habitat creation and landscape enhancement [1]. Traditional constructed wetland systems predominantly employ indigenous or well-adapted wetland plants, including emergent species such as Typha, Phragmites, Scirpus, and Cyperus. These plants are selected because they can tolerate waterlogged, anoxic soil conditions where ordinary land-plants would fail. These plants have extensive fibrous root systems that play an important role in wetland treatment performance by stabilising the substrate, promoting sedimentation, and creating microscale redox gradients. Oxygen release which occur from roots into the rhizosphere, improves aerobic microbial activity, supporting processes such as nitrification, while adjacent anoxic zones support denitrification and other anaerobic transformations. Additionally, the macrophytes break down nutrients such as nitrogen and phosphorus into their biomass, thus acting as a temporary sink that helps reduce nutrient concentrations in the treated effluent [2, 3]. Despite the effectiveness of conventional plant-based systems, they also have some essential limitations. The process of uptake of essential nutrients by plants is often seasonal, controlled by growth cycles and climatic conditions. Long-term pollutant removal depends heavily on microbial and substrate-mediated processes rather than on plant assimilation alone. It has been observed that many wetland plants show limited tolerance to high contaminant loads, salinity, drought, or toxic industrial effluents. This phenomenon can reduce system efficiency under extreme or variable operating conditions. Latest innovations in biotechnology and genetic engineering have created new possibilities for improving the performance of constructed wetlands by using engineered plants with modified or enhanced properties. Genetically modified plants can be designed so as to exhibit improved phytoremediation, including increased uptake and accumulation of nutrients, heavy metals, or organic pollutants. Increasing root exudation patterns may stimulate beneficial microbial communities, hence strengthening coupled plant–microbe remediation pathways. In addition, genetically modified plants can be modified for greater resistance to abiotic stresses, including salinity, drought, and changing water levels. This, in turn, allows wetlands to function more reliably under tough environmental conditions. If such engineered plants are introduced, it can have the potential to increase sustained biomass production, improve contaminant removal efficiency, and expand the applicability of constructed wetlands across a wider range of wastewater types and climatic regions [4]. However, their use also generates essential ecological and regulatory considerations. This can include biosafety, gene flow, and long-term impacts to the ecosystem. Consequently, biotechnology offers promising opportunities to enhance constructed wetland systems. But its application must be guided by meticulous risk assessment and integrated system design to ensure environmental sustainability [1, 5-8].

2. Role of Plants in Constructed Wetlands

The large aquatic plants, commonly grown in constructed wetlands, are called macrophytes. These plants are vital to treatment performance as well as hydraulic and habitat functions. These plants used in constructed wetlands carry out several important functions. Solar energy is captured by chlorophyll during photosynthesis. The carbon dioxide is captured by these plants from the atmosphere. By utilising this solar energy, these macrophytes assimilate this inorganic carbon from the atmosphere into organic molecules such as glucose,

carbohydrates and other biomass. This phenomenon supplies the energy source for bacteria and fungi. These macrophytes also cause a reduction in wind speed near the water surface. Dense wetland vegetation reduces light penetration in the water column. The limited light suppresses the growth of phytoplankton, since these phytoplankton depend on sunlight for photosynthesis. The presence of these plants in constructed wetlands also reduces water flow velocity, which creates better conditions for sedimentation of suspended solids and also increases the contact time between water and the plant surface areas. These macrophytes play an important role in stabilising the soil surface of the constructed wetlands, since penetration of their root systems reduces the formation of erosion channels [2] (Brix, 2003). In vertical flow constructed wetlands, the growth of roots of these plants helps to reduce clogging [9]. The submerged stems and leaves of macrophytes provide a surface area for the development of biofilms and also the growth of photosynthetic algae, bacteria and protozoa [10]. Similarly, the roots and rhizomes, buried in the soil, also support attached growth. These biofilms help in organic matter degradation and nutrient transformations [9]. The roots of the emergent and submerged macrophytes leak oxygen into the rhizosphere. This creates oxidised microsites in the anoxic media, which in turn stimulates aerobic degradation of organic matter and nitrification [8, 11]. Roots exude organic compounds (often estimated as a fraction of fixed carbon), which can serve as electron donors for denitrifiers, thereby supporting nitrate removal in anoxic microsites of subsurface-flow wetlands [3, 9]. Ammonium, nitrates and phosphorus are assimilated by the plants into their biomass. The emergent macrophytes are capable of storing a considerable amount of nitrogen and phosphorus per m2. Their nutrient uptake capacity ranges between 30 and 150 kg P per hectare per year and between 200 and 2500 kg N per hectare per year [5, 11]. The emergent and rooted floating-leaved macrophytes absorb inorganic nitrogen (both ammonium and nitrate) from porewater in the root zone; free-floating macrophytes take up N directly from the water column. The long-term removal of phosphorus is mainly accomplished by sorption / precipitation onto the substrate . Phosphorus uptake occurs mainly as orthophosphate, taken up primarily through roots from sediments or substrates. Uptake via leaves and stems is generally limited in emergent species, but becomes more important in submerged macrophytes, which can directly assimilate phosphorus from the surrounding water. Also, the phosphorus uptake through submerged leaves and stems is generally smaller, except in submerged species [2, 12]. A study conducted on constructed wetland macrophytes reported nutrient uptake ranging from 8.6–9.3 g Total Phosphorus and 29.1–48.2 g Total Nitrogen for the tested species in the experimental units. This data shows that the nutrient uptake varies strongly with species and biomass production. Macrophyte species can notably affect ammonia and phosphorus removal, with one laboratory study reporting up to 82% ammonia removal and 76% soluble phosphorus removal in Cyperus papyrus[13, 14].

Genetic modification can make wetland macrophytes much more useful and tolerant to harsh conditions, by giving them stress tolerance, better resource use, and targeted pollutant-removal abilities. By adding genes for drought and salt tolerance, improved root systems, or stronger antioxidant defenses, GM plants can keep taking up water and nutrients, and maintain healthy growth, even when conditions are tough. They need less fertilizer because they use nutrients more efficiently. These stress-tolerance characteristics help macrophytes survive in wastewaters with high metal content, salt, or other harsh conditions, and they also support long-term wetland treatment [4, 15-18]. Genetic modifications can also directly improve pollutant removal. For example, boosting genes for metal transport or detoxification increases the plant’s ability to extract heavy metals. The breakdown or transformation of toxic substances can be done by adding bacterial enzymes . Other changes, like increment of root surface area or release of more root exudates, can stimulate helpful microbes in the soil. Together, these improvements speed up microbial processes like nitrification, denitrification, and organic matter breakdown. As a result, constructed wetlands with GM macrophytes can remove tough pollutants more effectively, while also reducing the need for pesticides and machinery, lowering nutrient runoff, preserving soil, and supporting more sustainable treatment and land use.

3. Assessing the Nature of Genetically Modified Plants

With the emergence of Genetically Modified (GM) plants, there was a considerable transformation in modern biotechnology. These GM plants, on one hand, improved several deficiencies of normal plants, while on the other hand, they also introduced some problems. Hence, before introducing the engineering application of these plants, it becomes essential to investigate their beneficial uses as well as disadvantages.

3.1. Advantages

Genetically modified plants can be prepared to tolerate abiotic stresses such as drought and salinity, which can normally restrict plant growth and their productivity. These stresses disrupt water uptake, nutrient balance, and cellular metabolism in conventional plants. Genetic engineering may incorporate certain genes that confer stress tolerance or can enhance plant performance under adverse conditions. These types of modifications may increase water usage efficiency, cause improved root structure, or enhance osmotic adjustment within plant cells[4, 18]. Saline ecosystems have the capacity to control ion transport functions, that help to lessen toxic sodium accumulation while preserving ionic balance. The genes capable of tolerating stress also help protect cellular elements by activating antioxidant and protective pathways. Due to this, some important physiological processes such as photosynthesis and respiration continue to function effectively. This helps GM plants to carry out normal growth and biomass production even under limited water availability or high salinity. So, these plants can be cultivated within environments that would otherwise be unsuitable for conventional crops. If there are observed improvements in nutrient use efficiency through genetic modification, then it allows GM plants to assimilate nitrogen, phosphorus, and micronutrients more effectively. This reduces fertiliser requirements and minimize nutrient runoff into water bodies. Insect-resistant and disease-resistant GM plants often require significantly reduced chemical pesticide use, thereby lowering agricultural input costs and mitigating environmental contamination from insecticide residues. Herbicide-tolerant GM crops can help in more efficient and selective weed control, thereby allowing farmers to adopt eco-friendly farming practices, preserving soil structure, reducing soil erosion and enhancing carbon sequestration, causing diminished reliance towards mechanical farming practices [18, 19]. In constructed wetlands, GM plants may also provide direct treatment advantages by improving the uptake, translocation, and sequestration of heavy metals. Literature on wetland grasses and transgenic phytoremediation shows that introducing genes such as merA and merB, metal transporters, phytochelatin-related genes, or metallothionein pathways can enhance tolerance to toxic metals and increase remediation potential. This is particularly relevant for wetlands treating metal-bearing industrial effluents, where plant-assisted phytoextraction can complement sorption and substrate-based removal processes [4, 17, 18].

Another major advantage is improved breakdown of organic pollutants and xenobiotics in the rhizosphere. Some GM plants can be designed to express degradative enzymes in their tissues or roots. These enzymes can act on the pollutants directly, by oxidising, hydrolysing, or transforming contaminants into less harmful forms. Again, some other GM plants can stimulate microbial activity through greater root surface area, altered exudation, and enhanced oxygen release into the rhizosphere. However, many field studies have exhibited that the effect is often small or inconsistent, with soil type, season, and crop management usually having stronger influences than the GM trait itself. All these changes can promote aerobic degradation, nitrification, denitrification, and mineralisation of recalcitrant compounds, while also improving microbial colonisation on roots and litter surfaces [4,16,17].

3.2. Disadvantages and Challenges in Using Genetically Modified Plants in Constructed Wetlands

Despite their increased remediation potential, genetically modified (GM) plants in constructed wetlands for wastewater treatment present several significant disadvantages, which makes it hard for their wider acceptance and application as depicted in Figure 1.

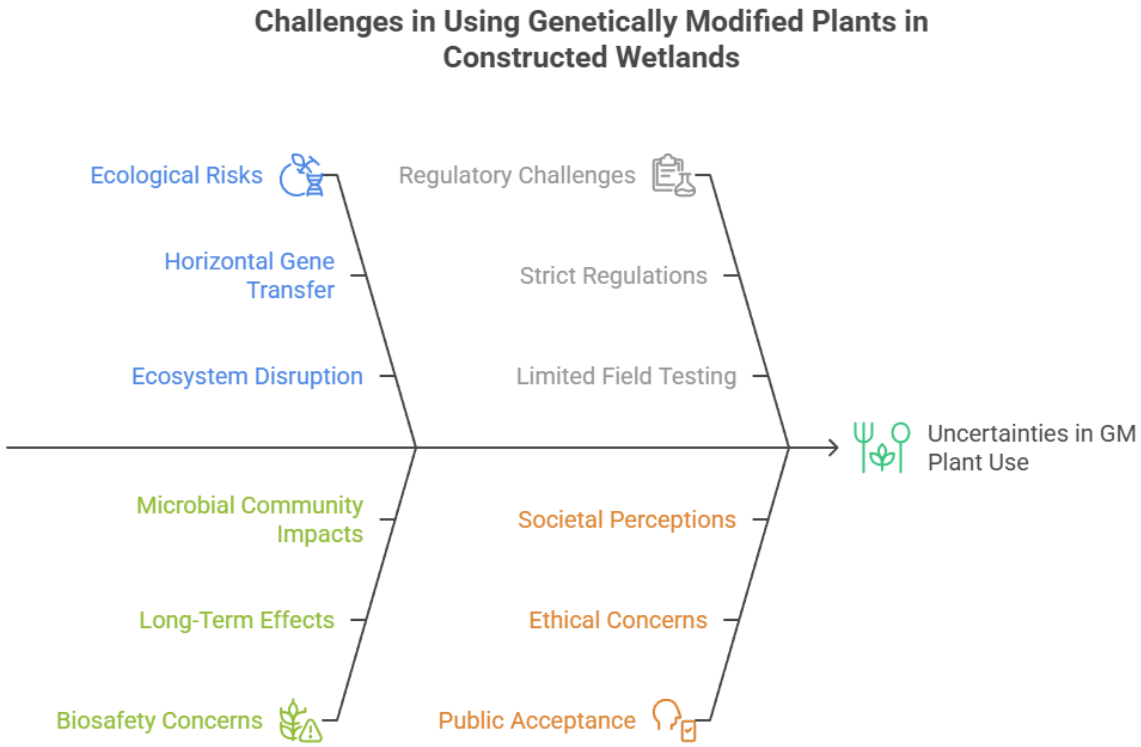


Fig. 1. Disadvantages and Challenges in Using Genetically Modified Plants in Constructed Wetlands

The primary concern is horizontal gene transfer (HGT), where transgenic DNA can be transferred onto non-target organisms including soil bacteria and wild plant relatives through transformation, conjugation, and transduction, potentially spreading antibiotic resistance genes used as selection markers [20, 21]. Cross-pollination can be prevented by using buffer zones between the GM and the non-GM plant of the same species. In genetically modified wetland plants, mitigation of horizontal gene transfer should integrate buffer zones, reproductive sterility, rhizome containment, and hydrological isolation to prevent spread within wetland landscapes. For example, in case of Phragmites australis and Typha latifolia, which can produce abundant wind-dispersed pollen and spread aggressively in wetland systems, we can observe that reproductive containment is especially important. For Canna indica, vegetative spread and site hygiene may be relatively more relevant than long-distance pollen movement, although both should still be considered. Biosafety risks are still not fully understood, as long-term ecological effects are not fully characterised, including adverse impacts on indigenous microbial communities important for nutrient cycling and wetland ecosystem functioning [22]. The persistence of transgenic DNA within aquatic environments poses additional concerns, as naked DNA from dead or damaged GM plant cells can remain intact when associated with sediment particles, creating opportunities for uptake by naturally competent bacteria in wastewater systems [21]. The major hurdles to GM plant deployment in phytoremediation programs are due to regulatory as well as public acceptance challenges, including strict biosafety regulations and limited field-testing permissions. The growth-stage-dependent effects of GM plants on microbial communities introduce inconsistency in treatment performance, as transgene expression varies seasonally and with plant development stages, affecting pollutant removal efficiency [20]. Additionally, antibiotic resistance marker genes may promote the development of resistant bacterial strains in biofilms and microbial communities within constructed wetlands under normal wastewater treatment stress conditions [21, 22].

4. Opportunities and threats of using genetically modified plants in Constructed Wetland Systems

There are several benefits due to the adoption of GM plants in constructed wetlands for treatment performance and system design. GM plants can be modified with genes that increase the uptake, sequestration, or metabolic breakdown of specific pollutants (e.g., heavy metals, nutrients, pesticides), hence improving removal efficiencies for target contaminants. In addition, enhanced stress tolerance allows wetlands to function under more contaminated, saline, or hydraulically variable conditions without notable loss of treatment efficiency. For a given effluent quality target, more efficient pollutant removal may reduce the required hydraulic retention time, overall system size, and associated land footprint. GM plants may also be designed to simultaneously support water purification, bioenergy or biomass production, and nutrient recovery, helping to enhance the value of the resource. Taken together, these traits suggest that GM plants could enable more compact, resilient, and multifunctional constructed wetland systems [7, 23].

Although it looks promising, a rigorous appraisal is required before deploying genetically modified plants in wetlands, due to several concerns. Outcrossing with wild relatives or the escape of transgenes may lead to unintended consequences, such as the creation of "superweeds" or altered interactions with non-target species [18]. Genetically modified plant species might disrupt microbial communities, food webs, or ecosystem processes within and beyond the wetland [24]. The fate and impact of transgene products such as Bt toxins in aquatic systems remain areas of limited study. Additionally, there might be unintended effects on non-target organisms in the treatment system, likely disruption of beneficial microbial communities essential for pollutant degradation, and regulatory issues regarding environmental release[4]. With respect to regulatory and public endorsement, the deployment of GM plants in open aquatic settings may create societal, ethical, and policy challenges [12, 25]. Public acceptance poses a major challenge towards incorporation of GM plants, since perceptions about GM plants differ between various countries regarding the importance and the associated risks. Several nations show reluctance towards using GM products, while companies prioritise profits beyond potential long-term problems. The ethical challenge is mainly regarding the interference with natural life processes, which raises the question of how to balance technological advantages against ecosystem integrity [24-26]. These concerns demand strict risk assessment protocols before deploying GM plants in wetland remediation applications.

5. Current Research and Prospects

As of now, genetically modified (GM) plants for constructed wetlands are mainly at the conceptual or mesocosm research stage, drawing heavily on more extensive transgenic phytoremediation work rather than full-scale CW applications. Current research focuses on introducing genes that can improve the performance of metal uptake, sequestration, or detoxification, as well as enzymes that speed up the degradation of organic pollutants like pesticides and industrial chemicals. Studies show markedly improved accumulation or transformation of target contaminants in soil and water systems, suggesting clear potential if these plants are integrated into CW hydraulics and configurations. The concept of using GM plants for augmented phytoremediation is scientifically feasible, though large-scale field data remain limited [11]. Risk assessment frameworks are being proposed to evaluate gene flow, ecological impacts, and monitoring strategies [12, 19]. To date, there is no specific regulatory framework worldwide that provides guidelines for using these GM plants in constructed wetlands for treating wastewater. Instead, each country follows its own rules regarding GMO biosafety, using GM plants on a case-by-case basis, with risk assessments for environmental safety, gene flow, and ecosystem impact. These GMO biosafety rules are a set of scientifically regulated management measures that are used to assess and minimise possible risks from genetically modified organisms to human health, animals, and the environment. For example, in the European Union, releasing genetically modified plants into nature requires strict approval under Directive 2001/18/EC, including safety checks and monitoring. This directive controls any outdoor release of modified plants, and for its introduction, official

permission, risk studies, and ongoing safety checks are essential. In case of India, genetically modified plants fall under general environmental laws, but till now there exists no specific rule for genetically modified wetland plants, meaning they need special case-by-case clearance. Although India in 2016 published a guideline document about the Environmental Risk assessment of Genetically Engineered Plants, but it is a general biosafety guidance for environmental release of GE plants, and has no mention about the prospects of using these genetically modified plants in a constructed wetland for wastewater treatment[27-29]. Current studies have shown that, the conventional constructed wetlands are cost-effective in comparison to the conventional treatment methods in a sewage treatment plant.GM plants may only be thought of in place of conventional macrophytes if they significantly outperform natural species in nutrient uptake and resilience. Cost involved in their research & development (R&D), biosafety concerns, and regulatory hurdles are at present quite high[30]. Thus, in spite of being superior in nutrient uptake capacity and resilience characteristics, their high initial R&D costs, ecological and regulatory risks and also unproven-ness does not make them attractive to be used in constructed wetlands till now.

6. Conclusion

Constructed wetlands offer a resilient, environmentally friendly solution for wastewater treatment, with macrophytes, substrates, and microbial communities working together to remove contaminants. The assimilation of genetically modified plants into these systems presents a promising option to enhance pollutant uptake, stress tolerance, and treatment efficiency, potentially reducing land requirements and expanding the range of treatable wastewater. However, questions regarding horizontal gene transfer, ecological impacts, and public and ethical acceptability point out the need for precaution. Future progress will depend on rigorous, long-term field studies, transparent risk–benefit evaluations, cost-effectiveness and the development of clear regulatory and monitoring frameworks before large-scale implementation.

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