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Synthetic Biology in Algal and Plant Systems for Enhanced Biosensing and Bioremediation

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A B S T R A C T

Environmental pollution by heavy metals, pesticides, pharmaceuticals, and endocrine-disrupting chemicals poses serious risks to ecosystems and human health. Synthetic biology offers powerful tools to engineer algae and plants for improved biosensing and bioremediation of these pollutants. This review provides a systematic overview of advances in applying CRISPR/Cas9 genome editing and metabolic engineering in microalgae and terrestrial plants to create "smart" biosensor organisms and highly efficient pollutant-degrading systems. We discuss how engineered algae and plants have been designed to detect environmental toxins (e.g., via fluorescent or colorimetric reporters) and to enhance degradation or removal pathways for contaminants including pesticides, pharmaceuticals, and endocrine disruptors. Key examples include microalgal strains with inserted genes for herbicide-degrading enzymes and CRISPR-edited plants with increased heavy metal uptake capacity. The performance of engineered algal vs. plant systems is compared, highlighting algae's rapid growth and suitability for aquatic environments versus plants' extensive biomass and root systems for soil remediation. We also address challenges in scaling up these bioengineered solutions, such as biosafety containment, regulatory hurdles, and the need for robust genetic toolkits in non-model species. Overall, synthetic biology is enabling the development of algae and plants as living biosensors and as sustainable agents for cleaning up environmental pollutants, with recent successes pointing toward their increasing role in environmental monitoring and remediation in the coming decade.

Introduction

Numerous pollutants, such as toxic metals, pesticides, pharmaceuticals, and endocrine-disrupting substances have been released into the environment by contemporary industrial and agricultural activities which involves the use of conventional physical and chemical remediation techniques that itself have drawbacks, such as secondary pollution or high energy costs (Yao, Li, Xie, & Yu, 2012). On the other hand, biological methods that use plants, algae, and microbes to remove or detoxify pollutants that are more economical and sustainable (Ayub *et al.,* 2025). The application of engineering principles to biology, or 'synthetic biology', is currently paving the way for the creation of customized organisms for environmental remedies (de

Lorenzo, 2022). Through the use of technologies like CRISPR/Cas9 genome editing and metabolic pathway engineering, scientists can either give plants and algae new functions or improve their innate capacity to process pollutants. As a result, the idea of "smart" biosensor organisms that can identify and manipulate particular chemicals has been developed (Borah, Singh, Chattopadhyay, Kaur, & Bari, 2024).

Because of their intrinsic roles in ecosystems and their capacity to absorb and metabolize a variety of substances, algae and higher plants are particularly appealing platforms for such interventions. Microalgae, which include Cyanobacteria and eukaryotic microalgae, are unicellular photosynthetic organisms that grow quickly in water and have the ability to accumulate organics or metals, providing a controlled system for treating wastewater (Mahlangu, Mphahlele, De Paola, & Mthombeni, 2024). Another such technique is known as phytoremediation which involves use of terrestrial plants to remove or stabilize pollutants from wetlands and soils because of their large biomass and root systems (Kafle *et al.,* 2022). Genetic engineering has been used to improve the performance of both systems. For instance, stress tolerance genes have been introduced to help algae survive in toxic wastewaters, and plant genes have been edited to increase heavy metal uptake (L. Tang *et al.,* 2017; Venegas-Rioseco, Ginocchio, & Ortiz-Calderon, 2021).

Synthetic biology tools for engineering algae and plants

The ability to precisely alter genes in plants and microalgae has been transformed by CRISPR/Cas9 genome editing and related technologies. Researchers can introduce new metabolic functions or disrupt genes that limit pollutant tolerance by using CRISPR/Cas9 to perform targeted knockouts or insertions. For example, a cadmium transporter gene in rice has been knocked out using CRISPR, resulting in plants that accumulate 90% less cadmium in grains (Yang ZHANG & HUANG, 2019). This illustrates how genome editing can produce safer crops or plants that are more appropriate for heavy metal phytoremediation. Although engineering efficiency varies by species, CRISPR/Cas systems in algae are increasingly being adapted for species such as Cyanobacteria and *Chlamydomonas reinhardtii* (V. K. Patel, Das, Kumari, & Kajla, 2023). With the creation of species-specific toolkit components, CRISPR application in algae is becoming easier by integrating promoters and selectable markers, but strong genetic tools are still lacking in many environmental algal strains (Spicer & Molnar, 2018).

Simultaneously, metabolic engineering techniques aim to introduce or improve biochemical pathways involved in the detection or degradation of pollutants. Scientists have inserted genes encoding microbial degradative enzymes into plants and algae using recombinant DNA techniques (Zhou *et al.,* 1994). New capabilities have been made possible by such transgenic expression, such as plants expressing a fungal laccase enzyme to oxidize endocrine-disrupting chemicals or algae modified to produce a bacterial enzyme that breaks down the herbicide atrazine (Kirby, 2010; Macellaro, Pezzella, Cicatiello, Sannia, & Piscitelli, 2014). Metabolic engineering frequently adds entire pathways or regulatory circuits, in contrast to CRISPR, which usually modifies already-existing genes. The development of a synthetic receptor circuit in plants that can identify small molecules is one noteworthy achievement. By creating ligand-binding domains that stabilize a reporter protein only when a target chemical is present, Mandell and associates created a modular biosensor system (Feng *et al.,* 2015), using this strategy they built Arabidopsis plants that light up via luciferase when they detect the drug digoxin, demonstrating that it is possible to detect pollutants or other compounds in plants. (Furuhata, Sakai, Murakami, Nagasaki, & Kato, 2020). These strategies are complemented by more advanced tools such as inducible promoters, gene switches, and protein engineering using CRISPR activation (CRISPRa) with dead Cas9 fused to activator domains to turn on genes in plants to enhance heavy metal sequestration pathways (Sarma *et al.,* 2021).

In microalgae, synthetic biology has also been facilitated by the development of standardized assembly toolkits (e.g., MoClo and Golden Gate systems) to rapidly assemble multi-gene expression vectors and insert reporter genes for biosensors or multi-enzyme degradation pathways in a single step (Hinz, Stenzler, & Poulain, 2022; Webster, Villa-Gomez, Brown, Clarke, & Schenk, 2024). Meanwhile, transformation methods such as Agrobacterium-mediated, electroporation, or biolistic delivery have also advanced to the point where it is possible to generate stable transgenic lines of some algae and most plants (Hwang, Yu, & Lai, 2017). Together, the recent progress in gene editing and pathway assembly over the last decade provides the framework for developing algae and plant lines that can be customized for specific environmental remediation tasks.

Engineered biosensors for environmental monitoring

The creation of whole-cell biosensors living things that react to particular pollutants by producing a detectable signal is an intriguing use of synthetic biology (C. Liu *et al.,* 2022). Plants and algae have been developed as biosensors that can detect the presence of pollutants in soil or water, effectively acting as early warning systems for environmental monitoring (Amaral *et al.,* 2024).

Biosensing in algal systems

Owing of their quick response and ease of estimating signals such as fluorescence in cell cultures, microalgae are an excellent choice for biosensors in aquatic environments and connecting pollutant-responsive genetic elements to reporter genes is a common method (Xu, Close, Sayler, & Ripp, 2013). For instance, genes encoding fluorescent proteins in *Chlamydomonas* have been fused with promoters that react to heavy metal exposure, causing the cells to fluoresce when metals are present (Rasala *et al.,* 2013). In a study, scientists produced a strain of *Chlamydomonas* that expressed a FRET-based metallothionein sensor, which detects the binding of heavy metals (Hg^{2+}, Cd^{2+}, etc.) by producing an energy transfer signal through fluorescence resonance (Dementyeva *et al.,* 2021). This made it possible to measure free metal ions within the algae, with mercury being more sensitive than other metals (Rajamani *et al.,* 2014). These genetically encoded sensors enable on-site, real-time water quality monitoring without the need for complicated equipment.

Another innovative design involved two strains of microalgae construction with different herbicide sensitivity. The method includes the biotransformation of the herbicide simazine with one genetically engineered algal strain to be resistant to simazine while another remained susceptible. Both were immobilised simultaneously and when simazine was present, the susceptible algae showed a sharp decrease in the production of photosynthetic oxygen, while the strain with resistance continued to function normally. By comparing their oxygen concentrations using an integrated O_2 sensor, the system selectively detected simazine in water, with a detection limit of approximately 12 mg per litre (Haigh-Florez, de la Hera, Costas, & Orellana, 2014). This clever comparative approach improved specificity by accounting for the general effects of stress.

In addition to fluorescence and oxygen, scientists have also used changes in chlorophyll fluorescence in algae as signals. Many pollutants cause measurable changes in the efficacy of photosystem II. Optical biosensors based on chlorophyll fluorescence inhibition were tested for metals such as Cd^{2+}, Cu^{2+} and Zn^{2+} (Durrieu *et al.,* 2006). Based on the measurement of the extinguishing of algal fluorescence after exposure to a water sample the overall toxicity was determined. However, the specificity remains restricted. Therefore, a trend towards genetic modification ensures specificity by inserting a bio-sensor circuit that activates only in the presence of a specific chemical (Guo, Li, & Zuo, 2024). Recent work has demonstrated that algae-based sensors can be used with much improved sensitivity for the pesticide atrazine (Ballen *et al.,* 2025). *Chlamydomonas* cells were confined in microglials to stabilize their optical signal and linear detection of atrazine was achieved in a range of 0.04 to 100 mg per ml. This level of sensitivity and stability showed that synthetic biology combined with materials engineering made it possible to make algal biosensors work in the field (Y. Liu *et al.,* 2023).

Biosensing in plant systems

The use of plants as environmental biosensors offers interesting possibilities for in situ monitoring over large areas such as sentinel plants field that change colour or luminescence when pollutants are present (Petri, Cordon, Diz, González, & Lagorio, 2024). Plants respond naturally to stress, but synthetic biology can make these responses more specific and visible. A pioneering example is the work of a team at the Wyss Institute that has engineered Arabidopsis plants to glow when given the progesterone or digoxin compounds (Klein, 2024). They have developed a synthetic ligand binding domain that stabilises the fused luciferase enzyme when bound to digoxin, causing the glow in the plant (Shinohara, Moriyama, Ohyama, & Matsubayashi, 2012). This system achieved more than 50-fold increase in luminescence when digoxin was applied, showing that whole plants can be programmed to detect small molecules (Klein, 2024). Such proposals could in principle be extended to environmental poisons by imagining trees or grasses emitting a fluorescent or colour-changing signal when they absorb a pollutant such as TNT or a banned pesticide.

Plant sensors for chemicals and explosives are being investigated by researchers. In one DARPA-funded project, spinach plants were equipped with nanoparticle sensors that worked by transmitting an alert when the plant roots came into contact with nitroaromatic explosive compounds (Wong *et al.,* 2017). That method exemplifies the idea of "smart plants" as non-invasive monitors, even though it employed nanotechnology and was not solely genetic. Plants have been genetically altered to produce microbial sensor proteins. To produce a visible reporter, transgenic tobacco has been tested using bacterial mercury-responsive operon components (e.g. GFP) in soil tainted with mercury (Haque, Zeyaullah, Nabi, Srivastava, & Ali, 2010). A visual "phytosensor" has also been created by introducing artificial promoters that are sensitive to arsenic or other heavy metals into model plants (Yasmeen, Wang, Riaz, Zhang, & Zuo, 2023). These studies demonstrates that plants can be given detection abilities that are typically found in bacteria that have been engineered.

One benefit of plants is that their signals may be seen from a distance via satellites or drones if the signal is a change in pigment or fluorescence. One suggested use is for deep-rooted plants close to industrial areas or susceptible water sources. If these plants sense that a chemical, such as an organic solvent or pesticide, has contaminated the groundwater, they could, for instance, turn a portion of their leaves into a distinctive color as a warning (Negri, Hinchman, & Gatliff, 1996). Businesses and defense organizations are interested in such applications, even though they are still in the experimental stage.

There are ongoing efforts to engineer hardy weeds, such as mustard plants, to function as living sensors for pollutants or chemical warfare agents (Nepal *et al.,* 2024). The difficulties include preventing false positives and guaranteeing specificity. However, the instruments of plant synthetic biology such as synthetic transcription factors and gene switches are better equipped to deal with these (W. Liu & Stewart Jr, 2016)

Engineered systems for bioremediation of pollutants

Synthetic biology is being used to eliminate or neutralize pollutants in addition to sensing them (Petri *et al.,* 2024). Scientists hope to produce plants and algae that either hyperaccumulate pollutants for removal or break down harmful substances into innocuous products by altering metabolic pathways (Yaashikaa, Devi, & Kumar, 2022). Such techniques are in progress using algal and plants as model to treat a contaminated site.

Bioremediation in algal systems

By absorbing nutrients and some organics, microalgae already aid in the treatment of wastewater, through engineering their potential to address stubborn pollutants has been greatly expanded (Abdelfattah *et al.,* 2023). Introducing particular bacterial catabolic enzymes into algal cells is one effective tactic. For example, a plant pathogen's glutathione S-transferase (GST), which catalyzes the breakdown of herbicides, was engineered into *Chlamydomonas reinhardtii* (Chatzikonstantinou *et al.,* 2017). Under the same conditions, the transgenic algae demonstrated a significant improvement in the degradation of the rice herbicide penoxsulam, achieving ~93.6 percent removal as opposed to only ~52 percent removal by wild-type cells (Ismaiel, El-Ayouty, & Al-Badwy, 2019). This shows that an alga's capacity to detoxify a pesticide can be increased by a single additional enzyme. To combat cyanide pollution, scientists have also given algae bacterial cyanide hydrolase (cyanase) genes. A Cyanobacterial cyanase gene into *C. reinhardtii*, allowed the algae to withstand and eliminate up to 150 mg/L of cyanide, a significantly higher level than what unmodified strains could withstand. The engineered algae transformed toxic cyanide into less hazardous compounds, offering a novel biological treatment for industrial cyanide waste (Sobieh *et al.,* 2022).

Additionally, engineered microalgae have been developed to break down medications and endocrine disruptors (Ravikumar, Velmurugan, John, & Selvarajan, 2024). Natural algae are however unable to completely metabolize chemicals found in personal care products, synthetic estrogenic compounds, and other substances (X. Li, Shen, Jiang, Xi, & Li, 2024). Pathways to bridge this gap have been added through synthetic biology. To speed up the breakdown of endocrine disruptors like bisphenol A and different paraben preservatives, genes encoding laccases and peroxidase enzymes which have the ability to degrade a wide variety of persistent organic pollutants have been expressed in algal cells (S. K. S. Patel *et al.,* 2021). In a 2025 study, several parabens were completely removed within 7 days when *Scenedesmus* and *Chlorella* modified to secrete laccase were co-cultivated, while non-modified algae only partially removed the parabens in the same amount of time (Rezvani, 2025). Enzymatic biodegradation supplementing the algae's natural uptake pathways is responsible for the improved performance (Shukla, Pradeep, & Singh, 2025).

Degradation of pesticides has received a lot of attention. In addition to the herbicide, the breakdown of the persistent insecticide lindane is a notable example. LinA2, a dehydrochlorinase enzyme involved in lindane degradation, was overexpressed in the Cyanobacterium *Anabaena* through genetic modification. In 6–10 days, the modified *Anabaena* was able to totally eliminate 10 ppm of lindane from solution, something that the wild type could not accomplish due to insufficient enzyme activity (Chaurasia, Adhya, & Apte, 2013). In a different study, a *Cyanobacterium* (*Synechococcus elongatus*) was engineered with a triphenylmethane reductase gene to break down the toxic dye malachite green. Following engineering, the Cyanobacteria not only adsorbed the dye, as the wild type did, but also broke it down, achieving 99.8 percent degradation (Han *et al.,* 2020). These illustrations highlight how algae or Cyanobacteria can become potent bioremediation agents for particular organic pollutants by introducing a single effective degradation pathway.

Genetic enhancement has also helped with heavy metal remediation using algae. Algae naturally use peptides like phytochelatins and metallothioneins to sequester metals and bind them via cell surface groups (Chugh, Kumar, Shah, & Bharadvaja, 2022). Engineered algae can however accumulate even more metals by overexpressing these peptides or transport proteins. For example, attempts are being made to engineer algae that overproduce binding polypeptides to sequester metals internally and to overexpress metal transporters in microalgae to increase uptake of arsenic or mercury (Haoujar, Altemimi, Abrini, & Cacciola, 2025; Leong & Chang, 2020). Although there are currently few case studies of CRISPR-edited algae for metals, it is theoretically simple to inhibit metal efflux pumps in order to stop metal release and trap more metal in biomass (Sincak, Šoltisová, Luptakova, & Sedlakova-Kadukova, 2023). This strategy might produce algal strains that hyperaccumulate heavy metals for safe disposal and subsequent harvesting.

Mineralization of plastic and pollutants is another frontier. Algae can now contribute to the breakdown of plastic waste with the help of synthetic biology. Researchers have created a bacterial PETase enzyme in *C. reinhardtii* that breaks down PET plastic. PET films are partially degraded in culture by *C. reinhardtii* and *Phaeodactylum tricornutum* (Dissanayake & Jayakody, 2021; Kim *et al.,* 2020). These experiments demonstrate the potential of algal platforms to address even solid pollutants like plastics by secreting the right enzymes, despite their current slow pace. As more effective variations are created through enzyme engineering, algae could be employed as solar-powered factories that discharge these enzymes into contaminated streams.

Engineered microalgae and Cyanobacteria have shown the ability to biodegrade pesticides, dyes, pharmaceuticals, and even plastics more effectively than their wild counterparts. They offer a versatile, aquatic-based remediation approach, often yielding rapid treatment cycles due to algae's fast growth. Many challenges such as maintaining engineered traits in large outdoor ponds and preventing engineered strains from escaping into natural ecosystems are still a concern, but the progress to date is encouraging. As indicated in Figure 1, genetic modifications can dramatically boost pollutant removal metrics for algae in laboratory studies, paving the way for improved algal bioreactors for wastewater polishing and pollutant-specific treatments.

Bioremediation in plant systems

Plants have long been used in phytoremediation, leveraging their natural capacity to extract, sequester, or detoxify pollutants in soil and water. However, many pollutants either are not readily taken up or not effectively metabolized by wild-type plants. Genetic engineering is overcoming these limits by augmenting plants with new metabolic pathways or by boosting their tolerance to toxic environments (Wang & Demirer, 2023).

Organic xenobiotics, or substances like explosives, solvents, or persistent pesticides that plants typically cannot completely decompose, have been a primary focus of transgenic plant research (Abhilash, Jamil, & Singh, 2009). The development of plants that express a mammalian cytochrome P450 enzyme to break down volatile organic pollutants was a significant accomplishment. In a study, the broad-spectrum degradative enzyme human CYP2E1 gene was inserted into tobacco plants and poplar trees. The ability to metabolize pollutants like trichloroethylene (TCE), a common groundwater pollutant and industrial solvent, was acquired by the CYP2E1-expressing plants. In lab experiments, the transgenic poplars mineralized TCE into CO_2 and innocuous metabolites at a rate up to 640 times faster than that of non-engineered plants (Doty *et al.,* 2007). These GM poplars were shown to be able to endure in a TCE-contaminated area and considerably lower TCE levels in groundwater plumes after a six-year field trial (E. Legault, 2013). This explains how a single potent enzyme enables plants to tackle pollutants that they otherwise could not affect.

Enhancing plant degradation of pesticides and explosives is another accomplishment. Compounds like 2,4,6-trinitrotoluene (TNT) or organophosphate pesticides are typically difficult for plants to break down. Scientists have created transgenic plants that detoxify explosives in soil by introducing bacterial genes that break down these substances (Kalafut *et al.,* 1998). For example, tobacco and Arabidopsis were genetically modified with a bacterial nitroreductase gene which enabled them to both survive in TNT-contaminated soil and change the TNT into less phytotoxic derivatives (Kurumata *et al.,* 2005; L. Zhang, Rylott, Bruce, & Strand, 2017). Similar to this, it has been demonstrated that plants that express the organophosphate hydrolase enzyme degrade common organophosphate insecticides and analogs of nerve agents in their tissues, thereby serving as living filters (Thakur, Medintz, & Walper, 2019). Even though some of these studies go back a decade or two, more recent research is building on them by using CRISPR to stack multiple traits and better expression strategies.

Genetic engineering of plants to produce hyperaccumulators or tolerant varieties has been thoroughly investigated for heavy metal remediation (Kozminska, Wiszniewska, Hanus-Fajerska, & Muszynska, 2018). Overexpressing genes related to metal uptake, transport, or sequestration is one strategy. For instance, overexpressing the Arabidopsis ATP-binding cassette transporter (AtATM3) in Indian mustard (*Brassica juncea*) produced plants that accumulated considerably more mercury and arsenic in their shoots compared to wild-type plants (Gupta, Kumar, Janeja, Prakash, & Anand, 2024; Pilon-Smits *et al.,* 1999). Similar to this, plants can increase the chelation and storage of cadmium or arsenic in vacuoles by overexpressing yeast or bacterial phytochelatin synthase genes, which lessens toxicity and permits greater accumulation (Y. Li *et al.,* 2004; Su *et al.,* 2020). Increased uptake of arsenic and cadmium from hydroponic solutions was demonstrated by transgenic tobacco overexpressing the rice metal transporter OsMTP1, indicating its potential for cleaning Cd-contaminated soils (N. Das, Bhattacharya, & Maiti, 2016). In a different study, Arabidopsis was given a metallothionein gene (SaMT2) from a selenium-hyperaccumulator plant. As a result, it showed greater tolerance to Cd and Zn and accumulated more of these metals in its tissues than the wild type. These changes enable plants to flourish in contaminated soils and draw out more pollutants, which speeds up and improves phytoremediation (J. Zhang *et al.,* 2014).

Phytoextraction has also been improved through the use of genome editing. CRISPR can be used to eliminate plant genes that restrict metal uptake rather than introducing foreign genes. It has been demonstrated that CRISPR/Cas9 deletion of the OsNramp5 transporter in rice significantly lowers cadmium uptake into grain (Luo, Liu, Yang, Zhu, & Huang, 2023). The opposite could be done for bioremediation, which would force more metals to migrate to harvestable shoots by eliminating genes that cause metals to be locked in roots. Currently, scientists are trying to develop "super-accumulator" plants by disrupting the regulation of metal transporters (Z. Yang *et al.,* 2022). Using CRISPRa to upregulate genes for glutathione production, for instance, could improve a plant's ability to deal with and sequester specific organics or metals (McLaughlin *et al.,* 2015). Another CRISPR tactic is to activate transcription factors that trigger the plant's own detox processes. Although these applications are still in the early stages of development, they show how CRISPR-based precision breeding can enhance transgenic technology.

The most successful plant remediation frequently results from a combination of microbial and plant action. Exudates or enzymes that encourage soil microbes to break down contaminants can be released by engineered plants (K. M. Yang, Poolpak, & Pokethitiyook, 2023). In addition to metabolizing pollutants themselves, poplars modified with CYP2E1 may also release oxidative metabolites that are further broken down by soil bacteria, leading to full mineralization (M. Li *et al.,* 2024). The bioavailability of heavy metals for uptake or microbial transformation in the rhizosphere can also be increased by plants that have been genetically modified to overproduce root exudates such as citrate or malate (Ma *et al.,* 2022). In order to create a cooperative pollutant degradation network, synthetic biology approaches occasionally take into account building plant-microbe consortia or engineering endophytic bacteria alongside the plant host (Timofeeva, Galyamova, & Sedykh, 2023).

Genetically modified plants have demonstrated improved ability to remove a range of contaminants, including heavy metals with transport and sequestration genes, explosives and pesticides with bacterial catabolic genes, and volatile organics with cytochrome P450s (Shourie, Mazahar, & Singh, 2024). Unlike algae, they can reach pollutants buried in soil and cover large areas. However, compared to microalgae, plants typically operate more slowly and are influenced by environmental factors and seasonal growth. Trials in the field with GM poplars show practical viability, but they also emphasize on the necessity of making sure that added genes do not adversely affect the plant's growth or allow it to spread to wild relatives (Sozoniuk & Kowalczyk, 2022). Phytoremediation biosafety concerns are being addressed by developments in inducible expression, which only activates the remediation genes when necessary, and chloroplast genetic engineering, which limits transgenes to organelles that do not spread pollen (Y. Zhang, Tian, & Lu, 2023).

Comparative analysis of algal vs. plant systems

Both plant and algal platforms have unique advantages for biosensing and bioremediation, and they can be seen as complementary rather than antagonistic approaches. The main distinctions and factors to take into account between plant-based and microalgae-based methods in environmental applications are outlined in Table 1 (Parmar, Kumar, Neha, & Srivatsan, 2023).

Practically speaking, an engineered microalga could be used to treat factory effluent in a closed photobioreactor. For instance, a strain of *Chlorella* designed to break down pharmaceutical residues in hospital wastewater (Kumari, Kumar, Kothari, & Kumar, 2024). Algal biomass would be gathered, disposed of or processed after the algae sensed and degraded drug molecules, releasing clean water (Y. Yang *et al.,* 2023). However, in an engineered plant system, GM poplar trees could be planted around a landfill site's perimeter. The poplars' deep roots could absorb leachate that contains solvents or heavy metals and either metabolize them or sequester them in wood, keeping the pollutants from getting to nearby groundwater or farmland. To make sure they are actively remediating, these trees could also be observed using remote fluorescence sensing. (James, 2024).

Notably, plants and algae can be combined. For example, to maximize the removal of a wide range of pollutants in a constructed wetland, aquatic plants such as duckweed or reeds could be used alongside algae in the water (Wu *et al.,* 2023). While the algae break down organic pollutants, the plants may accumulate heavy metals, resulting in a multi-layered treatment ecosystem (Ayub *et al.,* 2025). Such systems could be further integrated through synthetic biology, such as creating a symbiotic relationship in which algal endosymbionts reside within plant tissues to promote degradation (Andrianantoandro, Basu, Karig, & Weiss, 2006).

Thereby, the choice between using plants or algae or both will depend on the situation. The plants are better at landscape level remediation and situations where pollutants are scattered in soils or difficult to access groundwater, while algae are better at controlled wastewater treatment situations and for quick pollutant degradation in liquids (Ugwuanyi, Nwokediegwu, Dada, Majemite, & Obaigbena, 2024; Zaman, Ali, & Akhtar, 2024). Synthetic biology benefits both systems in a way that plants have been given new pathways and enhanced uptake through transgenes and gene editing, while algae have experienced significant improvements in degradative capabilities through metabolic engineering (B. D. Das & Bhattarai, 2025; Kumar *et al.,* 2023).

Challenges and future prospects

Although the potential of synthetic biology in algal and plant systems is great, several challenges must be overcome before the use of these engineered biosensors and bioremediators becomes a common practice. There are genuine concerns regarding the release of genetically modified organisms (GMOs) into the environment and their eventual effects and gene flow. Although algae can be maintained within closed reactors, but scaling-up poses risks of escape. Plants on other hands, if introduced into open fields, could potentially contaminate through the dissemination of pollen or seeds. Future applications are expected to benefit from approaches that utilize non-replicating clones, transgenes contained within organelles, or expression conditioned to specific events to address these issues (Beacham, Hand, Pink, & Monaghan, 2017). Obtaining regulatory and social acceptances for environmental applications of GM algae and plants will require safety and benefit assurance.

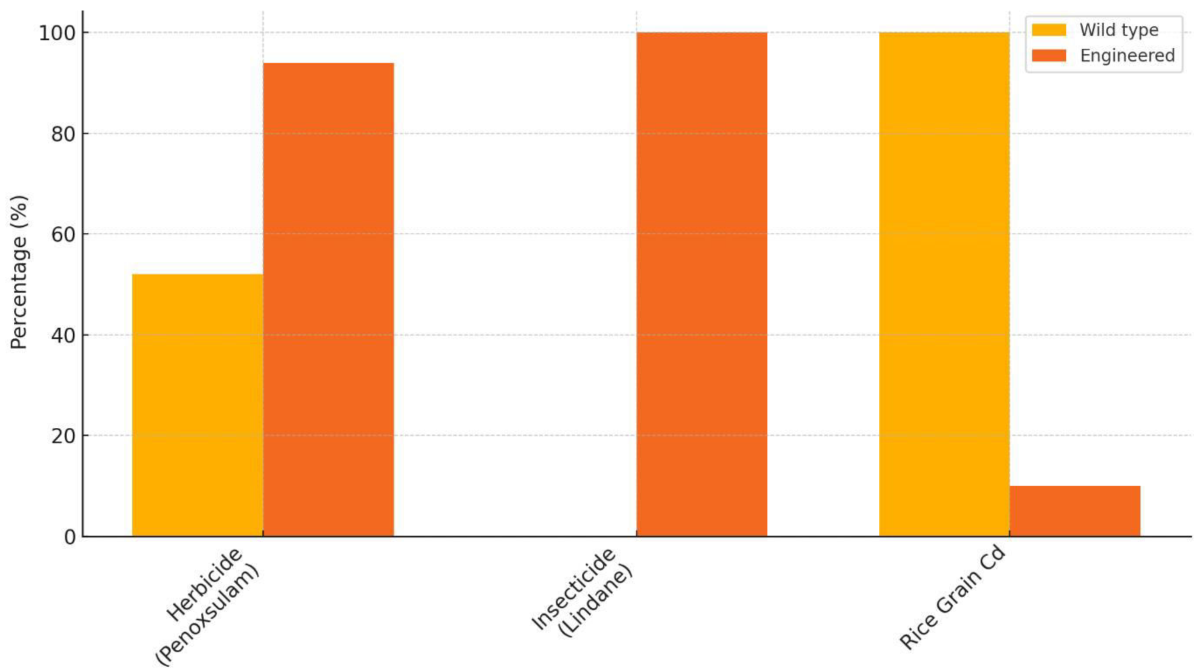
While laboratory experiments frequently consist of one-generation tests. Natural environments could cause engineered algae to lose their plasmids or engineered traits if there is a fitness. Engineered plants however pose a disadvantage that could have lower fitness than natural ones in harsh polluted soil or could decrease gene expression with time. To remedy this problem, genetic engineers are making genetic circuits that are highly stable and self-regulating.

Table.1 Comparison of engineered algal vs. plant systems for biosensing and bioremediation**.**

Parameters	Algal Systems (Microalgae/Cyanobacteria)	Plant Systems (Terrestrial/Aquatic Plants)
Typical Habitat & Deployment	Aquatic environments such as ponds, bioreactors, wastewater, ideal for treating contaminated water or effluents in controlled settings (Chandran *et al.,* 2025).	Terrestrial and aquatic ecosystems such as soils, wetlands, riverbanks, ideal for in situ remediation of contaminated soils, sediments, or as constructed wetlands for water (Helfield & Diamond, 1997).
Growth Rate & Biomass	Very fast growth like doubling in hours, easy to scale in tanks and small microscopic size but can form dense cultures. Biomass can be harvested continuously (Richmond, 2003).	Slower growth in weeks to months for full yield, large biomass like roots, shoots covering wide area. Once established, can continually extract pollutants, biomass harvested periodically at season's end (Evangelou, Papazoglou, Robinson, & Schulin, 2014).
Genetic Engineering Tools	Developing but species-dependent. Model algae (*Chlamydomonas, Chlorella*) have good toolkits like transformation, CRISPR, plasmids, but many wild strains are less tractable. Easier to maintain clones in contained systems (Muhammad *et al.,* 2024).	Well-established for many species especially crops. *Agrobacterium*-mediated transformation and CRISPR editing routinely used in crops and model plants. However, field release of GM plants is tightly regulated (Rahman, Khan, Ullah, Ahmad, & Raza, 2024).
Biosensing Capabilities	Rapid real-time response in water with changes in fluorescence, luminescence, O_2 output which can be measured electronically. Suitable for continuous monitoring of water quality and quick detection of toxins or pollutants in effluents (Gruiz & Fenyvesi, 2017).	Capable of longer-term monitoring over large areas. Signals such as color change, fluorescence can be visualised or detected via imaging. Useful for indicating soil or groundwater contamination, though response may be slower in hours to days (Chaerle & Van Der Straeten, 2001).
Bioremediation Mechanisms	Absorb nutrients, metals, and some organics from water. Engineered enzymatic pathways can mineralize pollutants in water. Cell surfaces bind pollutants such as metals, dyes which can then be collected with biomass. Best suited for liquid-phase and dissolved pollutants (Ncibi, Mahjoub, Mahjoub, & Sillanpää, 2017).	Roots uptake contaminants like metals, organics and translocate to shoots, which can be harvested. Plant enzymes metabolize pollutants in roots and in leaves. Roots immobilize contaminants, preventing leaching/erosion. Suited for both soil and water pollutants via roots in water or soil (Basit, Shah, Ullah, Muntha, & Mohamed, 2021).
Advantages	Can be cultivated in controlled reactors. It allows for fast reproduction and allows quick evolution or selection of tolerant strains. It provides less land use, can be deployed at site of wastewater Contains systems which minimize gene escape, harvested biomass can be processed (e.g., for energy or safe disposal) (Rani, Gunjyal, Ojha, & Singh, 2021).	Roots access deep or diffuse contamination, and planting over a site is relatively low-cost passive remediation. Public perception of using "plants" for cleanup is generally positive, and plants can enhance ecosystem restoration at a site. It can target pollutants in situ without excavation (e.g., heavy metals in soil, organic toxins in groundwater). It allows well-understood agronomic practices for planting, harvesting, and breeding improved varieties (Kuppusamy, Palanisami, Megharaj, Venkateswarlu, & Naidu, 2016).
Challenges	For environmental release, concerns about non-native or engineered microalgae escaping into natural waters and affecting ecosystems. Some algae are sensitive to fluctuations in water quality (pH, temperature, competing microbes),	Generally slower to see results Root uptake is limited for certain pollutants e.g., hydrophobic organics that don't translocate well. Engineered pathways may not reach full potential if the pollutant doesn't enter the plant readily. Risk of transgene spread via pollen or seeds have strict regulatory oversight for field use of

	engineered strains must maintain function under field conditions. Biomass separation after treatment can be costly for large volumes; dead algal cells may release toxins back if not managed. Genetic tools for many pollutant-degrading species (e.g., certain cyanobacteria) still lag behind model organisms (Subashchandrabose, Ramakrishnan, Megharaj, Venkateswarlu, & Naidu, 2013).	GM plants involving mitigation strategies like chloroplast engineering or sterile cultivars are often needed. Plant health can be adversely affected by high pollutant load, so engineered plants must balance remediation with tolerance (Singh, Ghai, Paul, & Jain, 2006).

Figure.1 Examples of enhanced pollutant remediation achieved through genetic engineering.



Bars compare performance of wild-type vs. engineered organisms for three cases. "Herbicide (Penoxsulam)" shows percent of herbicide removed by wild vs. engineered Chlamydomonas reinhardtii (engineered strain expressing a degrading enzyme achieves ~94% removal vs. ~52% in wild type) (Ismaiel *et al.,* 2019). "Insecticide (Lindane)" shows percent lindane degraded by wild vs. engineered cyanobacterium (engineered Anabaena expressing linA2 achieves complete removal, whereas wild type has negligible degradation) (Govindasamy *et al.,* 2022). "Rice Grain Cd" shows relative cadmium accumulation in rice grains as a percentage of an unedited control (CRISPR knockout of OsNramp5 transporter in rice results in <10% of the cadmium uptake of wild type, dramatically reducing grain Cd levels) (Li Tang *et al.,* 2017). Higher bars are better for removal efficiency, whereas lower bars are better for contaminant accumulation.

They can also apply directed evolution or adaptive laboratory evolution on engineered bacteria to end up with more stable bacteria in stressful environments. They can also link traits such as pollutant degradation to survival such as giving energy advantage so that engineered bacteria are still under selective pressure regarding the trait (Webster *et al.,* 2024). Some of these constructed pathways require improvements in terms of efficiency. For example, a plant that can clean high amounts of heavy metal pollution could do so very slowly can take years to clean up an area. There could be inefficient enzyme activity in algae in terms of reaction rates, so that they didn't even scratch the surface of plastic degradation by producing the PETase-producing algal strain (Di Rocco *et al.,* 2023). Current research is underway to make improvements through protein engineering to produce more efficient enzymes to operate in planta or in vivo, and even to make use of synthetic microbial consortia to work in conjunction with algal or plant strains. Higher specificity of biosensors is another area for needed improvement to make sure they are accurate and do not send off false warnings, combining inputs through synthetic biology. An example of it is to require both pollutant inputs to send off an 'AND' signal, could lead to biosensors specific to a given chemical pattern or 'fingerprint' (Feng *et al.,* 2015).

One of the huge gaps in research is the application of small-scale laboratory data on a field scale. Currently, very few studies including GM poplar for TCE clean-up have been executed under natural conditions (E. K. Legault *et al.,* 2017). Natural conditions include factors such as microorganism competition, natural predators/grazers, natural climate, as well as a combination of contaminant concentrations. Designed algae in an open pond could be challenged by natural algae for scarce resources or grazed upon by zooplankton without protection by closed systems or special conditions. Designed plant species could be challenged by natural conditions like drought or lack of nutrients, affecting their application for contaminant clean-up. There will be a clear use of both biotechnologies, specifically environmental engineering designs like closed systems for algae, irrigation for plant clean-up sites combined with synth-bio.

Future research in biosensing and bioremediation is bound to combine bioscience with other technologies, such as data and electronic systems (Lea-Smith *et al.,* 2025). Plant biosensors can be networked together with distant IoT systems that receive the signals generated by plants, indicating the need for certain areas to be cleaned. Algal bioreactors can also be networked with sensors that show the levels of certain pollutants. These sensors can then control the conditions, such as the addition of certain nutrients, light, and CO_2, to ensure maximum efficiency in the degradation process. There is also the combining of engineered pathways of various organisms, such as bacteria, fungi, algae, and plants, to form a treatment train that can handle a mixture of pollutants (Janpum *et al.,* 2025).

In conclusion, the field of synthetic biology is quickly turning algae and plants into highly efficient biocleansers. Using genome-editing techniques such as CRISPR/Cas9 and metabolic engineering approaches and new designs of genetic circuits, scientists have managed to produce model organisms like algae and plants with high abilities to detect and clean environmental pollutions compared with their non-engineered natural counterparts. Microalgae has particularly emerged as one of the most efficient biocleansers against wastewater containing pesticides, pharmaceuticals, and endocrine disruptors, and many heavy metals and has already made its first steps towards biodegradation of plastics. At the same time, synthetic biology has widened applications of another biotechnological method of phytoremediation and has turned its focus to bioremediation of organic environmental pollutions such as solvents and explosives and to accumulation of heavy metals from soils.

Algae and plant systems each come with their own set of benefits, and depending on the pollution situation, they can be selected for use. Algae boast of their rapid growth and controllability, suited for closed systems like industrial wastewater treatment or waterborne biosensors. They can reach and endure in wilderness areas, suited for remediating polluted lands and operating as natural sensors for monitoring water quality.

In the future, we can see an environmental remedy box featuring “green” technologies like algal bioreactors for wastewater treatment facilities, fields of pollutant-sensing and pollutant-converting trees for protecting groundwater, and maybe floating “sewage-chasing” mats of designer aquatic plants for revamping eutrophic and polluted water basins.

To achieve this vision, some challenges relating to biosafety, regulatory requirements, and scalability have to be managed. In addition, there is a responsibility to engage with society and endeavors to win their confidence in using genetically engineered organisms for environmental cleanup. Perhaps most significant is a continuing research effort to optimize such organisms, making them more efficient, able to survive and operate well in a real-world setting, and avoid any unforeseen consequences in an ecosystem. As research continues to evolve and progress, it is widely perceived that within the next decade, genetically modified algae and plants would be found at the mainstream of bio-sensing and bioremediation techniques for monitoring and cleaning up the environment.

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Conflict of Interest

The authors declare that there are no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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