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Review

# Going beyond improving soil health: cover plants as contaminant removers in agriculture

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**Agriculture faces the increasing demands of a growing global population amid simultaneous challenges to soils from climate change and human-induced contamination. Cover plants are vital in sustainable agriculture, contributing to soil health improvement, erosion prevention, and enhanced climate resilience, but their role in contaminant management is underexplored. Herein we review the utilization of cover plants for remediating contaminants such as metals, organic pollutants, nitrate, antibiotics, antimicrobial resistance genes, plastics, and salts. We explore phytoremediation strategies – including phytoextraction, phytodegradation, and phytostabilization – in cover plant management. We highlight the challenges of selecting effective cover plants and the need for biomass removal of non-biodegradable contaminants, and we advocate incorporating phytoremediation concepts into sustainable agricultural management practices beyond nutrient cycling and climate resilience.**

## Highlights

Climate change and human contamination activities play a dual role in agricultural production, which leads to food shortages.

Aside from improving soil health, cover plants have the potential also to reduce contaminant levels in agricultural soils and products.

Cover plants and their associated rhizobiomes are still largely underexplored for their contribution to contamination management in current agricultural practices.

Several contaminants can potentially be remediated with cover plants, such as metals, organic pollutants, nitrates, antimicrobial resistance genes, plastics, and salts.

Cover plants may reduce the contaminant load of cash crops via phytoextraction, phytostabilization, phytodegradation, and phytovolatilization processes.

## Cover plants: promoting healthy soils and reducing contaminant stressors

To combat the pressing challenges posed by climate change, the widespread utilization of cover plants in agriculture has emerged as a crucial strategy [1]. **Cover plants** (see Glossary), including **cover crops**, offer a multitude of benefits to agriculture (Figure 1A), enhancing **soil health** [2] by preventing erosion and compaction, improving soil structure, water and air infiltration, and crop root growth. They also contribute to nutrient management by absorbing excess nutrients, reducing nutrient runoff, and enhancing nutrient availability for subsequent crops [1]. Additionally, cover plants suppress weeds by competing for sunlight, nutrients, and space, thereby decreasing the need for herbicides [3]. Despite their own need for water, cover plants may aid in moisture retention, generating and conserving water on an ecosystem scale and potentially reducing net irrigation requirements. Cover plants also foster above- and below-ground biodiversity by providing habitat and food for beneficial insects, macro- and microorganisms, promoting natural pest control [4]. Cover plants, especially as continuous cover, also promote the soil microbiome [5]. Their root systems create diverse microhabitats of different pH, temperature, moisture, organic plant residues, and rhizodeposits that foster microbial proliferation and diversity [6]. Furthermore, cover plants enhance climate resilience through carbon sequestration and mitigation of greenhouse gas emission [7]. Properly managed with **cash crop** rotation, cover plants ultimately enhance crop yields [8].

Planting cover plants in mixtures enhances their benefits compared with single-species plantings, improving ecosystem functions and increasing resilience to pests, diseases, and environmental stressors [9]. Mixtures exert a strong positive impact on the soils due to increased carbon availability, varied root exudates, and thus more diverse habitat conditions [10]. The selection of specific cover plants is based on factors such as climate, soil type, prior and subsequent crop type, rotational regime, growing season, nutrient requirement and provisional abilities, pest and disease resistance, management practices, and water requirement, aligning with the intended benefits throughout the agricultural season [11].

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However, agriculture faces additional challenges, including contamination by metals, persistent organic pollutants, nitrate, salinity, plastics, antibiotics, and antibiotic resistance [12,13]. These contaminants adversely affect agricultural systems, causing soil degradation, aquifer pollution, crop contamination, and impaired microbiome functioning, potentially leading to economic losses. Over time, these impacts culminate in the deterioration of soil health, undermining its ability to balance essential functions such as nutrient cycling, water regulation, and carbon sequestration, ultimately reducing the provision of critical ecosystem services that sustain agricultural productivity and environmental resilience. Conventional physical and chemical soil clean-up technologies are often cost- and time-intensive, disruptive to the environment themselves, and impractical for large-scale agricultural fields. A promising approach to address contaminant challenges in agriculture is phytoremediation, encompassing techniques like **phytoextraction**, **phytostabilization**, **phytodegradation**, and **phytovolatilization** (Figure 1B). To ensure high-quality yields of cash crops, phytoremediation approaches need to be pursued by cover plants either relieving cash crops of contaminant loads in fallow seasons or simultaneously. Notably, there is a knowledge gap regarding the intersection of cover plants and their phytoremediation potential.

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Herein we critically evaluate the current state of knowledge on using cover plants as phytoremediators in agriculture for each class of contaminant (Table 1), aiming to close the identified gap, providing valuable insights into harnessing cover plants as effective agents for contaminant control in agriculture, and merging known benefits of cover planting with phytoremediation concepts.

## Non-beneficial metal and metalloid removal by cover plants

Metals and metalloids (here referred to as metal/loids) of no beneficial use to plants and animals are problematic contaminants in agriculture due to their non-biodegradable nature, persistence in the environment, toxicity at low concentrations, and ease of transfer from soil to root and subsequently through the food chain [14]. Metals are of geogenic origin [15] and thus are omnipresent in soils [16]. Elevated levels in agricultural soils often result from mobilization through anthropogenic activities such as industrial processes, mining, urbanization, and agrochemical use [14,17]. Once taken up by crops, metallic contaminants interfere with basal physiological functions, ultimately reducing yields and the quality of edible parts [18,19]. Cover plants show promise for mitigating the impacts of metal/loids in agricultural systems (Figure 2A), though they have not yet been intensively and consistently investigated for such functionality. Two primary concepts are approached for metal/loids with a non-volatile phase: phytoextraction and phytostabilization.

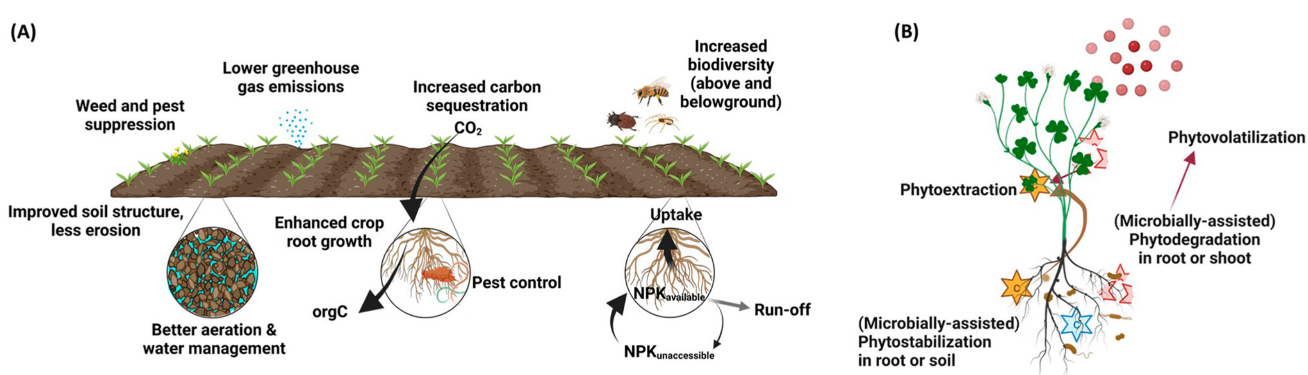


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Figure 1. (A) Current perception of benefits that cover plants provide for agriculture. (B) Different phytoremediation strategies for soils (partly assisted by microorganisms) that are classically employed for contaminated sites. The goal of the review is to propose merging known benefits of cover planting with phytoremediation concepts. Figure created with BioRender.

Table 1. Examples of cover plants that have shown potential for phytoremediating metals/metalloids, organic contaminants, and nitrate in soils

| Cover plant | Contamination | Mechanism | Refs |
|---|---|---|---|
| *Ageratum conyzoides* | Cd | | [96] |
| *Echinochloa colona* | Pb, Zn, Cu, and Cd | | [96] |
| *Calendula officinalis* | Cu | | [13] |
| *Calendula officinalis* | Cu | | [96] |
| *Perotis indica* | Ni, Cd, and Cr | | [13] |
| *Euphorbia hirta* | Cd | | [96] |
| *Eleusine indica* | Cd | | [13] |
| *Helianthus annuus* | n-Alkanes and PCBs, Cr, Pb, and Zn | | [97] |
| *Helianthus annuus* | Cr (VI) | | [15] |
| *Sorghum bicolor* L. | Pb, Cd, Zn, and Cu | | [98] |
| *Trifolium repens* | Cd, Pb, and Zn | | [25] |
| *Zea mays* | Mg | | [99] |
| *Cannabis sativa* | Cr | | [100] |
| *Helianthus annuus* | Zn | | [99] |
| *Nicotiana tabacum* | Cd | | [99] |
| *Secale cereale* L. | Total N, $NO_3^-$-N and $NH_4^+$-N | | [101] |
| *Glycine max* | PFBA, PFHxA, PFBS | | [102] |
| *Cannabis sativa, Helianthus annuus, Brassica juncea* | PFAS | | [103] |
| *Crotalaria juncea, Helianthus annuus* | Carbaryl insecticide, 1-naphthol | | [104] |
| *Cannabis sativa* | Fungicide metalaxyl-M, EDC, BPA | | [105] |
| *Glycine max* | PFOA, PFOS | | [24] |

Abbreviations: BPA, bisphenol A; EDC, endocrine disruptor; PCB, polychlorinated biphenyl; PFAS, per- and polyfluoroalkyl substances; PFBA, perfluorobutanoic acid; PFBS, perfluorobutanesulfonic acid; PFHxA, perfluorohexanoic acid; PFOA, perfluorooctanoic acid; PFOS, perfluoro-octanesulfonic acid.

Phytoextraction uses metal/loid-hyperaccumulating plants which absorb metal/loids through their roots and translocate these contaminants to above-ground biomass, where they accumulate at higher concentrations than in roots [20]. This method depends on specific plant traits such as exudate production, associated microbes, and the ability to take up, accumulate, translocate, sequester, and detoxify metal/loids [21]. Phytoextraction also depends on soil biogeochemical properties and environmental conditions [22]. However, traditional metal/loid-hyperaccumulators are often slow-growing, shallow-rooted, and produce low biomass [23]. Cover plants, with their rapid establishment, large canopy formation, and deep root systems, present a viable alternative, especially when exhibiting some degree of metal/loid tolerance. For instance, in vineyards, cover plants (*Avena sativa, Trifolium incarnatum, Chenopodium* sp.*, Vicia villosa, Secale cereale*, and *Brassica napus* L.) have been shown to reduce copper concentrations in topsoils [24]. Sunflower (*Helianthus annuus*) and clover (*Trifolium* spp.) were also found to effectively store nickel or cadmium in above-ground tissues, making them suitable for phytoextraction [25].

Phytostabilization of metal/loids in agricultural soils can be particularly effective when using cover plants as **intercrops**. In that case, they compete with cash crops for metal/loid uptake, thereby lowering metal/loid loads in cash crop products. Examples include sorghum (*Sorghum vulgare*) immobilizing bioavailable nickel in its roots, as well as *Mucuna cinereum* and *Mucuna aterrima*

## Glossary

**Cash crop:** the main crop grown primarily for sale to return a monetary profit.
**Cover crop:** a plant grown primarily to manage the agroecosystem and also harvested for monetary benefit alongside the cash crop.
**Cover plant:** a plant grown primarily to manage the agroecosystem as a non-harvested plant, although it could also be harvested as a secondary crop (the definition includes cover crops). Here it is defined as a plant planted temporally between consecutive cash crop cycles.
**Green manuring:** terminating cover plants while still green, and leaving them on the field to recycle nutrients from the biomass into the soil.
**Intercrop:** a special type of cover plant that is simultaneously grown with the cash crop in the same field and may or may not be harvested.
**Phytodegradation:** the breakdown of contaminants within plant tissues and the rhizosphere through metabolic processes.
**Phytoextraction:** the process in which plants absorb contaminants from the soil through their roots and translocate them to their above-ground tissues, where they can be harvested and removed.
**Phytostabilization:** the process in which plants immobilize contaminants in the soil or within roots, thereby reducing their mobility and bioavailability.
**Phytovolatilization:** the uptake of contaminants by plants from soil or water and their subsequent release into the atmosphere as volatile compounds, either in their original form or after transformation into less toxic or non-toxic forms through metabolic processes.
**Saline soils:** soils that contain high levels of soluble salts, with an electrical conductivity of the saturated soil extract exceeding 4 dS/m, which can hinder plant growth by reducing water uptake and causing osmotic stress.
**Saltol gene:** a gene that confers tolerance to salinity stress by enabling plants to better balance ions in the root compartment, especially sodium ($Na^+$) and potassium ($K^+$).
**Soil health:** the capacity of soil to function as a living ecosystem, supporting plants, animals, and humans, while maintaining essential ecosystem functions and services such as productivity, water filtration, nutrient

stabilizing copper in their root systems, making them excellent choices for phytostabilization [26]. Additionally, intercrops can stimulate cash crops to develop deeper roots, physically bypassing metal/loids often present in the top 5 cm of the soil, so that exposure is only temporary during growth.

In conclusion, cover plants offer a sustainable approach to managing metal/loid contamination in agricultural systems through phytoextraction and phytostabilization. In terms of managerial implications for metal/loid phytoremediation, cover plants could remove metallic contaminants during fallow seasons or phyto-stabilize metal/loids using intercrops, necessitating farmers to weigh pros and cons of metal removal versus nutrient recycling during **green manuring** (Figure 3). Future research and field studies are essential to optimize phytoextraction during fallow seasons and phytostabilization of intercrops.

## Minimizing nitrate leaching to groundwater with cover plants

Nitrate is a naturally occurring ion essential for plant growth and a crucial component of the nitrogen cycle. However, excessive nitrate poses significant risks to both the environment and human health [27]. Water bodies connected to agricultural land suffer from nitrate contamination due to excessive fertilizer use, intensive livestock farming, and sewage disposal [28]. This prompted the European Union to introduce the Nitrates Directive (91/676/EC) in 1991 to mitigate and prevent water pollution caused by agricultural nitrates. Resource-efficient agricultural practices, such as precision farming and optimized fertilizer application, are vital for mitigating nitrate contamination and safeguarding soil and water quality. Additionally, cover plants efficiently scavenge and bind available (i.e., leachable) nitrogen, already representing a common sustainable management option to reduce nitrate leaching into groundwater, nitrate enrichment in cash crops, and $N_2O$ emissions [29,30] (Figure 2B, Table 1).

cycling, and resilience to environmental changes.
**Soil water:** the water present in the soil, which exists in various forms such as hygroscopic water, capillary water, and gravitational water.

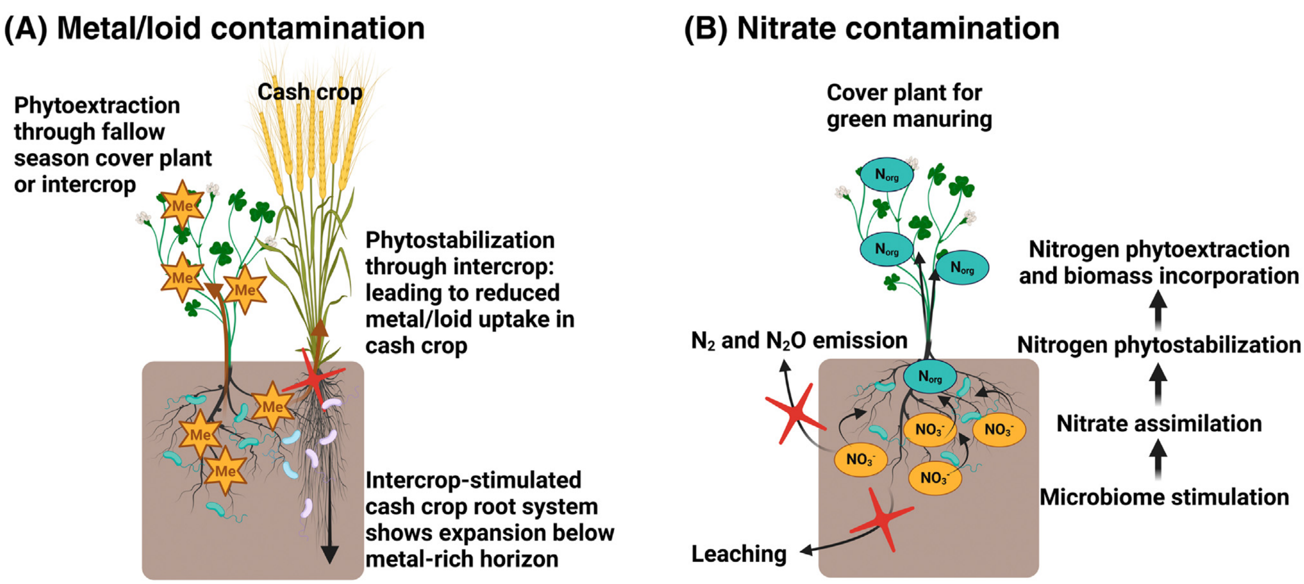


Figure 2. Conceptual schemes of possible phytoremediation strategies for cover plants and intercrops managing (A) metals, and (B) nitrate. (A) For metal/loid-contaminated soils, phytoextraction and phytostabilization approaches by cover plants or intercrops are most feasible and often explored in conjunction with microbial activities. (B) For nitrate-rich soils, leaching and nitrogen emissions can be reduced by stimulating rhizosphere microbial activities leading to nitrate assimilation in microbial and plant biomass, and thus, phytostabilization in roots and soil. Additionally, nitrogen is phytoextracted in the form of above-ground biomass assimilation. Green manuring circularly reuses assimilated nitrogen for subsequent cash crops. Figure created with BioRender.

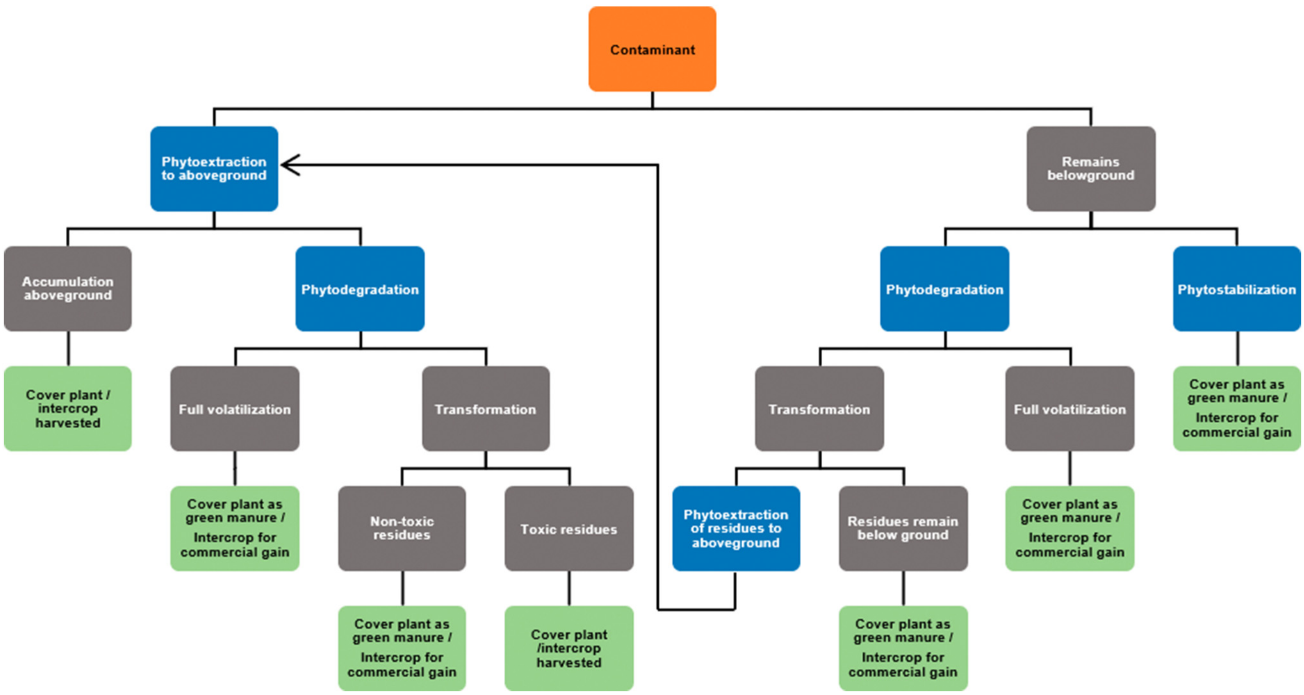


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Figure 3. Flow chart illustrating the various phytoremediation strategies of contaminants when using cover plants and intercrops to determine the fate of these cover plants and intercrops. (Orange = contaminant, blue = phytoremediation strategy, green = fate of cover plant/intercrop).

The extent of nitrate leaching reduction via phytoextraction and phytostabilization processes is strongly influenced by the cover plant species or species mixtures used. Two global meta-analyses revealed that non-legume species or species mixtures are particularly effective, with an average reduction of 56%, while leguminous cover plants show little to no reduction [29,31]. Within non-legumes, broadleaf species (54–77% reduction) outperform grasses (37–61% reduction). Cover-plant-enhanced microbial growth and activity improve nitrate conversion, immobilization, and mineralization processes through assimilation into microbial biomass or denitrification to nitrogen gases ($N_2$ or $N_2O$). Assimilated nitrogen is less prone to leaching and volatilization and may serve as an additional nitrogen pool for cash crops [32]. It was shown that soil nitrogen availability is increased when soil microbes become more active under warmer conditions in spring, which is based on the enzymatic release of amino acids from soil organic matter [33,34]. Timely sowing of cover plants after harvesting significantly reduced nitrate leaching [31]. This effectiveness can be influenced by temperature [35], annual precipitation [36], soil texture, and soil cultivation practices [30].

In summary, cover plants/mixtures positively reduce nitrate leaching and increase nitrogen use efficiency and circularity. Managerial implications for using cover plants or mixtures in nitrate management require careful consideration of plant and environmental conditions to avoid drawbacks [30]. Farmers must select species with appropriate carbon-to-nitrogen (C:N) ratios, as cover plants like grasses can cause nitrogen tie-up during decomposition, reducing its availability for subsequent cash crops. Proper timing of termination is equally critical; terminating too early or late can misalign nitrogen release with the next crop's nutrient demands, leading to inefficient uptake or nitrate leaching. During fallow periods of actively growing or green-manured cover plants, heavy rainfall can exacerbate nitrate leaching and trigger nitrous oxide (N O) emissions under waterlogged conditions, posing environmental challenges [32]. Addressing these factors ensures that farmers can optimize nitrogen management with cover plants while minimizing risks (Figure 3).

## Desalinizing with cover plants

More than 10%, or 833 million hectares, of arable land globally, are affected by salts, characterized by an electrical conductivity >4 dS/m and/or >15% of exchangeable sodium [12]. Agricultural soil salinization is increasing due to industry, deforestation, intensified agriculture, and climate-induced sea level rise [37]. Salt induces drought stress in plants, lowering crop production [38]. Physiological salt tolerance adaptations include moving away from salt sources, increased water uptake, higher lignin, and suberin contents in cell walls, vacuole compartmentalization, potassium and nitrate homeostasis, production of compatible solutes, and export through transporters, glands, vesicles, trichomes, and old leaves [39]. Cover plants, often overlooked in managing **saline soils**, can phytoextract and/or phytostabilize salts in soils, stimulate cash crops to root beneath saline topsoil layers, and manage **soil water** to reduce irrigation needs (Figure 4A).

Breeding and genetic engineering have made crops such as tomato (*Solanum lycopersicum*), wheat (*Triticum aestivum*), and barley (*Hordeum vulgare*) suitable for production in saline soils by overexpressing the **Saltol gene** [40]. Some crops occasionally used as cover plants, such as barley (*H. vulgare)* [41] and mixtures of millet [42], alfalfa [43], clover [44], and vetch [45], have been identified as salt-tolerant. Clover and vetch facilitate classic phytoextraction of salts [46] which could later provide biomass for bioenergy. Purposefully breeding or genetically engineering these cover plants with the Saltol gene has not yet been undertaken but could promote cover plants as a key tool in remediating salt-affected agricultural soils. Phytoextraction and salt tolerance

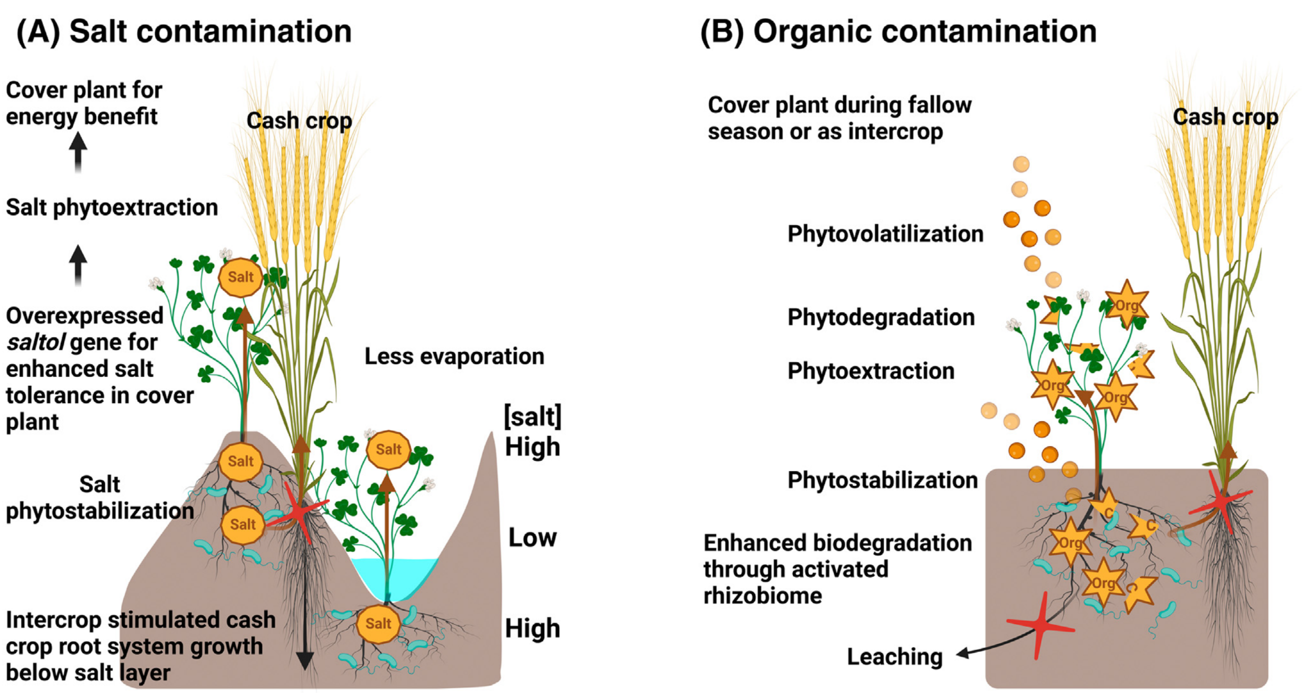


Figure 4. Conceptual schemes of possible phytoremediation strategies for cover plants and intercrops managing (A) salt, and (B) organic contaminants. (A) For saline soils, cover plants or intercrops can be used to stabilize salt in soils when grown on ridges and furrows. Simultaneous growth of cash crops on slopes would enhance root growth to access soil layers below the salt crust. Breeding or engineering the Saltol gene into cover plants would produce more resilient cover plants in saline soils. Cover plants can also phytoextract salts, which could be especially effective when simultaneously engineered for salt tolerance with the Saltol gene. (B) For organic contaminated soil, cover plants or intercrops facilitate enhanced biodegradation by activating the rhizobiome. Figure created with BioRender.

mechanisms operate through different processes, though both are crucial for managing salinity in plants. Phytoextraction involves the active uptake and accumulation of salt ions ($Na^+$ and $Cl^-$) from the soil into the plant's above-ground tissues [47], where they can be harvested, while salt tolerance, as conferred by the Saltol gene, enhances a plant's ability to survive in saline soils by improving cellular mechanisms such as compartmentalizing salts in vacuoles and maintaining osmotic balance [48]. Although these mechanisms are distinct, they could potentially complement each other. Genetic engineering of cover plants [49,50], such as clover and vetch, with the Saltol gene could improve their salt tolerance while maintaining or enhancing their ability to extract salts from the soil. Combining salt tolerance and phytoextraction could create more efficient plants for remediating saline soils; however, there is limited research on combining these two traits, and more studies are needed to determine whether the underlying mechanisms would be compatible and synergistic or whether one would interfere with the other.

In terms of managerial implications, cropping in saline soils is commonly performed with furrow agriculture, crops being planted on slopes where salt concentrations are lowest [51]. Salt-tolerant cover plants could be used to either remove salts during fallow periods or simultaneously with cash crop production as an intercrop [52]. For intercropping, cover plants should be planted on salt-rich ridges or furrows (Figure 4A). This might stimulate cash crop root growth, accessing deeper water sources lower in salts. Using cover plants as green manure could stabilize salts, reduce irrigation needs, and thus lower salt inputs [53]. Farmers need to decide on whether cover plant/intercrop removal or green manuring would be more beneficial for salt versus water versus nutrient management (Figure 3).

Cover plant–microbe interplay may also be crucial in managing saline soils. While cover plants sequester carbon from the atmosphere under salt stress [54], this carbon supports the growth of rhizospheric microbial communities, including mycorrhiza [55], soil bacteria [56], and endophytes [57]. This microbial activity improves soil structure, water retention, nutrient absorption, and rhizosphere expansion. Additionally, these microbes may immobilize and compartmentalize salts [58], helping to reduce salt uptake by cash crops.

## Organic contaminant degradation by cover plants

Pervasive organic contaminants in agricultural soils – including polycyclic aromatic hydrocarbons (PAHs), dioxins, triazines, and glyphosate – originate from pesticide use, industrial activities, and traffic [12]. Their impacts on agroecosystems vary, leading to adverse effects on crop yield and quality, and potential human health risks [59]. Some organic contaminants are degraded by microorganisms [40] and plants, including cover plants [60]. Cover plants, alone or with their rhizobiome, hold promise for integrating phytoextraction, phytostabilization, and phytodegradation (including phytovolatilization) strategies for organic pollutant management in agroecosystems, mitigating long-term pesticide effects (Figure 4B). These phytoremediation processes often work synergistically in various plant species, making it difficult to quantify the individual contribution of each process, but jointly they enhance the effectiveness for organic contaminant removal. The following examples illustrate the potential employment of these technologies for cover plants.

Indian mustard (*Brassica juncea*) is effective in phytoextracting and accumulating PAHs aboveground [61], and degrading pesticides like dichlorodiphenyltrichloroethane into less harmful forms [62]. Its extensive root network enhances soil aeration, making Indian mustard suitable for crop rotation during fallow periods or as an intercrop, mitigating long-term pesticide impacts. If pollutants are degraded without toxic grain accumulation, Indian mustard supports oilseed production; otherwise, strategic management is essential for complete pollutant removal simultaneously with nutrient management.

Vetiver grass (*Chrysopogon zizanioides*) showcases strong phytoextraction capabilities with its enhanced root uptake, translocation processes, and selective accumulation of hydrocarbons and pesticides in above-ground biomass [63,64]. It also excels in long-term phytostabilization with its deep, fibrous root system immobilizing contaminants. Vetiver grass synergizes with rhizosphere microbes to degrade, even volatilize, pollutants such as hydrocarbons, enhancing remediation efficacy. Despite its adaptability to various environmental conditions (extremes in water, temperature, pH, salinity, and metal co-contamination), vetiver grass has primarily been studied in industrial phytoremediation contexts, but its capabilities suggest potential as an off-season cover plant focused on pollutant management without significant nutrient contributions.

Sunflower (*H. annuus*) primarily remediates metals but also shows potential to extract and accumulate hydrocarbons [65]. It can also metabolize and volatilize herbicides such as atrazine, directly or aided by exudation-activated microorganisms [66]. While sunflower's agricultural remediation potential is recognized, current applications prioritize soil structure improvement and erosion control [67]. Research aims to optimize sunflower's phytoremediation through crop rotation and intercropping to maximize agronomic benefits.

Using Sunn hemp (*Crotalaria juncea* L.) during summer fallow periods and incorporating crop residues into the soil before planting the cash crop corn significantly reduced atrazine's desethyl atrazine (DEA) concentrations in corn fields over several years [68]. This reduction was attributed to Sunn hemp's ability to increase soil organic matter and stimulate the microbiome, recruiting a highly effective atrazine-degrading microbial community under repetitive herbicide applications. Concomitantly, DEA leaching into groundwater was reduced, and Sunn hemp could still be harvested for its seeds.

Some cover plants possess capabilities to extract, stabilize, and degrade/volatilize organic pollutants, and efforts have begun to integrate these abilities with traditional cover plant functions such as nutrient management and soil structuring. Tailoring managerial approaches to specific contamination scenarios necessitate decisions on intercropping versus cover planting, monocropping versus mixed cropping, and harvesting versus green manuring (Figure 3). If the cover plants transform contaminants into non-toxic residues, the cover plants can be sold or used as green manure (Figure 3). If the cover plants still contain contaminants or toxic residues, they have to be harvested and disposed of or used in alternative economic ways (energy production, construction). Screening and genetically optimizing current cover plants for organic pollutant management and enhancing interactions with aerobic and anaerobic bacteria, yeast, algae, and fungi [69] are crucial steps to assessing their phytoremediation effectiveness in field conditions.

## Preventing antimicrobial resistance spread with cover plants

Antimicrobial resistance (AMR) is a global health crisis exacerbated by excessive antibiotic use in human medicine and livestock production [70], with livestock consuming four times more antibiotics than humans [71]. Between 30% and 90% of administered antibiotics end up in manure due to incomplete animal metabolism [39]. Manure also contains antibiotic-resistant bacteria (ARB) that develop during hygienic, disease, and growth-support treatment [72,73], making manure a reservoir for antibiotic resistance genes (ARGs), with levels ranging from $2.1 \times 10^5$ to $7.8 \times 10^5$ copies/g [74]. When applied to fields, antibiotics and ARGs can transfer to edible crops, posing significant human health risks [75,76]. Mitigation strategies adapted to agricultural practices are nonexistent but urgently needed.

Cover plants have not been considered yet as tools for ARB and ARG removal in agriculture, albeit offering significant potential through two primary mechanisms: (i) reducing soil antibiotic concentrations, and (ii) limiting ARB establishment, thereby restricting horizontal gene transfer of ARGs into the soil microbiome.

Reduction in soil antibiotic concentrations is facilitated by both phytoextraction and phytodegradation/volatilization. Different plant species exhibit varying abilities to absorb antibiotics, depending on plant species and antibiotic class [75]. While research has focused on edible crops for food safety [77–79], cover plants show promise for phytoextraction when removed from the soil. However, the typically low antibiotic concentrations in plant tissues suggest that uptake may not be the primary removal pathway [77]. Instead, low antibiotic concentrations in rhizospheres of maize and manured vegetables [80,81] were attributed to enhanced biodegradation by a stimulated rhizobiome. Cover plants could potentially provide such a service through interactions with their associated microbiomes, although direct evidence has not yet been obtained. Fueling the rhizobiome with stimulating exudates [39] may enhance antibiotic degradation. Therefore, selecting cover plants based on their known ability to stimulate the soil microbiome, influenced by factors such as root exudate composition, could enhance their effectiveness in attenuating antibiotics.

Cover plants could also contribute to ARB and ARG management by stabilizing microbial communities against disturbance and invasion by alien species [82]. Studies consistently show lower ARB abundances in rhizospheres than in bulk soil, possibly due to increased selection pressures and limited establishment of ARBs from manure applications [39,83]. Growing cover plants before manure application may promote a soil microbiome more resistant to invasion, reducing the persistence of manure-borne ARBs and the frequency of horizontal gene transfer (Figure 5A).

Further research is essential to explore the managerial implications for cover plants in preventing the establishment and persistence of antibiotics, ARGs, and ARBs, especially in manure-fertilized

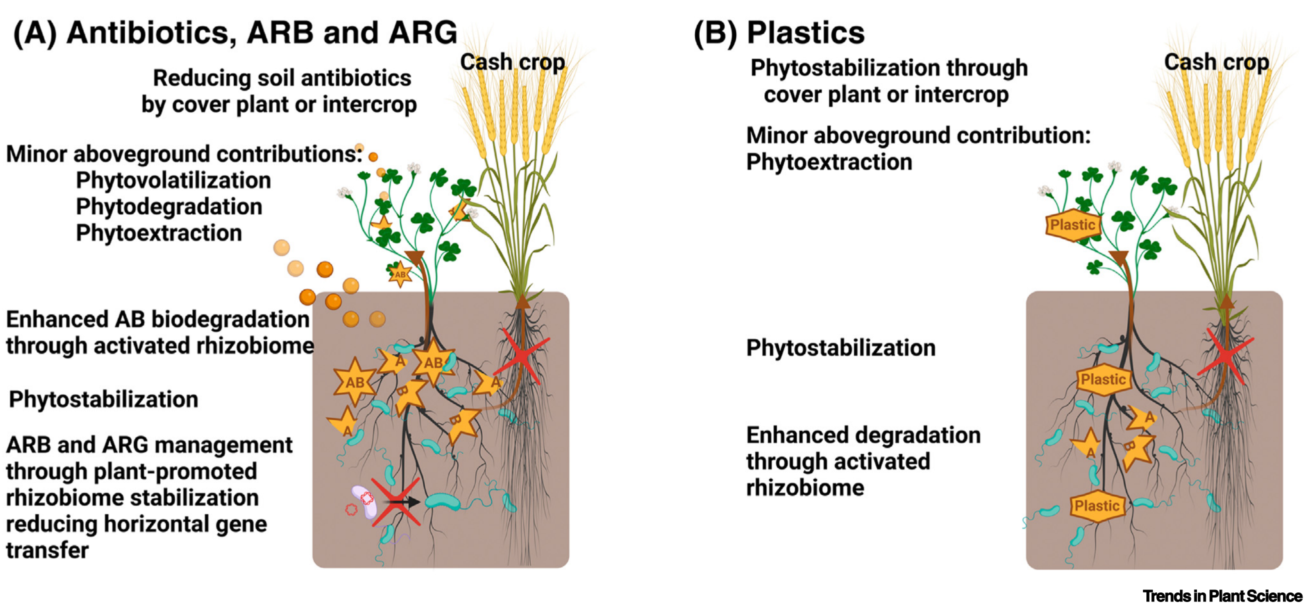


Figure 5. Conceptual schemes of possible phytoremediation strategies for cover plants and intercrops managing (A) antibiotics and antimicrobial resistance and (B) plastics. (A) For antibiotic, antibiotic-resistant bacteria (ARB) and antibiotic-resistance genes (ARG) contaminated soil, cover plants or intercrops offer enhanced antibiotic degradation and reduction in ARG transfer. (B) For plastic-contaminated soil, cover plants or intercrops enhance degradation below- and above-ground through activated microbiome and phytoextraction respectively. Figure created with BioRender.

agroecosystems. Moreover, integrating cover plants into agricultural practices for nutrient retention and subsequent incorporation as green manure can reduce manure application, thereby lowering environmental inputs of antibiotics, ARGs, and ARBs.

## Managing plastics with cover plants

Although 96% of studies on plastics focus on aquatic environments, terrestrial sources contribute 4–23 times more to macro-, micro-, and nano-plastics (here collectively referred to as plastics) [84,85]. Plastics enter agricultural land through diffuse inputs from human activities, including agricultural materials like film sheets, mulches, and fertilizer/pesticide packaging [86]. Composed of diverse organic polymers with additives, these plastics persist for decades, slowly degrading through UV light, Fenton reactions, and microbial activity [85]. In soil, plastics are consumed by soil fauna [87] and microorganisms [88], are taken up by plants [58], or they migrate into adjacent ecosystems [89]. Studies in agroecosystems show plastics adversely impact plant growth, soil microbiomes, and soil physicochemical properties [85,90,91]. Specifically, plastics disrupt plant–microbe interactions in the rhizosphere, influencing the amounts, composition, and activity of exudates and exoenzymes, thereby altering elemental cycling and plant nutrition [58].

Cover plants can potentially manage plastic inputs in agriculture, though this has not yet been studied. Using cover plants instead of plastic film sheets and mulches may lead to similar benefits, including weed suppression, soil water and temperature management, erosion control, and better cash crop root system growth and nutrient management [92]. However, further research is needed to determine whether cover plants, alone or with woody mulches, can match the benefits of plastic mulches, such as increased crop yields and early-season growth. Comparative studies are recommended to assess the benefits and drawbacks of plastic mulch versus cover plant management, including life cycle assessments of plastic inputs in both systems (Figure 5B).

Once plastics are present in agricultural lands, intercropped cover plants may offer effective phytoremediation by providing phytostabilization services, reducing or competing for plastic uptake by cash crops. In terms of managerial implications, cover plants could be used during fallow seasons to phytodegrade plastics by stimulating microbial activity and inducing microbial biofilm formation, which has been shown to increase plastic degradation. For instance, Janczak and colleagues [93] demonstrated in a pot study that plants such as miscanthus (*Miscanthus* x *giganteus*), rapeseed (*Brassica napus*), and willow (*Salix viminalis*), in combination with inoculated bacteria (*Arthrobacter sulfonivorans, Serratia plymuthica*) or fungi (*Clitocybe* sp., *Laccaria laccata*) selected for their hydrolytic activity and ability to grow on plastics *in vitro*, degraded polymer surfaces more effectively than non-amended controls. Moreover, microbial and plant-produced mucus may phytostabilize plastic degradation products in the rhizosphere, reducing their uptake into cash crops. However, the degradation of plastics into smaller particles could facilitate their uptake into cash crops or release phytotoxic chemicals, making plastic degradation in an agricultural context potentially problematic. Further research is needed to determine whether phytodegradation of plastics facilitates or prevents their uptake into cash crops and whether phytotoxicity occurs. These studies should be plastic type-specific and combine cover plant–cash crop systems in various soils and environmental conditions. Comparative field studies and long-term assessments are essential to evaluate the effectiveness and safety of this approach in different agricultural systems.

## Concluding remarks considering managerial implications

In conclusion, cover plants – and especially cover plant mixtures – offer a promising, sustainable approach for managing a wide range of agricultural contaminants through phytoextraction, phytostabilization, phytodegradation, and phytovolatilization (Figure 1B). Strategies for addressing legacy and prevalent contaminants such as metal/loids, organic pollutants, and nitrate are well established but require field verification (see Outstanding questions). By contrast, the potential of cover plants to tackle emerging contaminants such as ARG, plastics, and salts still needs to be identified, explored, and optimized before their application.

Managerial implications for handling barely to non-degradable contaminants (metal/loids, plastics, salts) need to be well thought through, as these substances often phytostabilize in the roots of cover plants and may re-enter the environment upon decomposition (Figure 3). To mitigate this risk, selecting cover plants with high contaminant retention or stabilization capacities is essential [94]. Additionally, crop rotation and species diversification can dilute contaminant concentrations and reduce their persistence in the soil–plant system. Regular soil monitoring is also vital to track contaminant dynamics in the rhizosphere and deeper soil layers, ensuring long-term effectiveness in phytoremediation efforts.

When plants extract non-degradable contaminants, the management of the harvested biomass is critical to prevent recontamination (Figure 3). Options such as bioenergy production – through combustion, gasification, or bioethanol production – offer potential, but require careful handling of residual contaminants. Phytomining is another viable strategy for recovering valuable metals, while controlled disposal methods like hazardous landfilling or high-temperature incineration provide safe containment. Emerging approaches, such as biopolymer production, may allow the use of biomass for bioplastics or industrial fibers, adding value to the remediation process. The choice of handling method depends on the type and form of contaminants, as well as economic feasibility and regulatory considerations.

Balancing the enhancement of soil health and nutrient management with contaminant remediation is crucial for maintaining crop yield and quality [95]. Despite their benefits, cover plants can introduce ecological challenges. In arid regions or during low rainfall periods they may deplete soil moisture, reducing water availability for subsequent crops. They can also harbor pests, diseases, or weeds, potentially affecting cash crops if not carefully managed. Moreover, improper selection or timing of cover plants can cause unintended nutrient imbalances, disrupting soil nutrient dynamics. For farmers, logistical challenges further complicate the adoption of cover plants. The costs of seeds, labor, and specialized machinery add to financial pressures, particularly when immediate returns are absent. Certain cover plants may require unique planting or termination techniques, necessitating additional investment. Furthermore, mismanagement in planting or terminating cover plants can interfere with cash crop schedules, diminishing overall farm productivity. To fully leverage the potential of cover plants for soil remediation, field studies tailored to diverse agricultural settings and cash crops are necessary. These studies can help refine strategies, balancing ecological benefits with practical implementation, and enhance the widespread adoption of cover plants in contaminant-managing sustainable agriculture.

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### Declaration of interests

The authors declare no competing interests.

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