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Integrated Phytoremediation and Biorefinery Approaches for Sustainable Recovery of Plant-Derived Bioactive Compounds

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Polluted farmland is often abandoned because its soil holds too much lead, cadmium or arsenic. Phytoremediation, the use of plants to clean contaminated soil and water, offers a low-cost alternative to digging and dumping, but the harvested plants carry the pollutants and are hard to dispose of. This article describes how combining phytoremediation with the biorefinery concept turns that waste into a resource. The harvest is processed in a cascade: valuable bioactive compounds such as polyphenols, flavonoids and essential oils are recovered first, the leftover biomass is converted into biogas, bioethanol or biochar, and metals are recovered from the ash at the end. Moderate metal stress can raise the production of some plant compounds, but too much metal can lower their quality, so crop choice and monitoring matter. The article also covers the benefits for rural income and sustainable development, and the challenges of safety, cost and regulation that remain. Together, these steps show how polluted land can give clean soil, renewable energy and income for farmers.

Keywords: phytoremediation, biorefinery, bioactive compounds, heavy metals, biomass valorisation, circular bioeconomy

Introduction

Picture a field that farmers gave up on because its soil holds too much lead, cadmium or arsenic. Now picture the same field growing plants that slowly clean the soil, with the harvest going into medicines, fragrances, antioxidants and biogas. That is the promise of joining **phytoremediation**, the use of plants to clean contaminated land and water, with the **biorefinery** concept, in which biomass is processed into several useful products, much as crude oil is in a refinery. Heavy metal pollution from mining, industry, urban waste and excessive agrochemical use is a serious environmental concern, and it endangers ecosystems, biodiversity and human health (Wijekoon, 2025). Removing and dumping polluted soil is costly and strips the land of its fertility. Phytoremediation offers a cheaper and gentler option, yet it creates a problem of its own: the cleaning plants end up carrying the contaminants, so large quantities of polluted biomass have to be handled safely (Wijekoon et al., 2025). Burning or dumping this material simply wastes the gain. The integrated approach treats this problem as a resource. Plants first clean the site, and the harvest is then processed in stages. High-value bioactive compounds are recovered first, energy and materials second, and metals last. Linking phytoremediation with biorefining adds value to both and makes metal recovery easier (Hejna, 2021). This article explains how the approach works, which products it can yield, and what still has to be solved before farmers can use it.

Phytoremediation: plants as green cleaners

Plants can clean a site in several ways, depending on the contaminant, its availability to the roots, and the local environment (Table 1). The best-known method is phytoextraction, where roots absorb metals and carry them to shoots that can be harvested. Other methods include keeping metals locked in the root zone (phytostabilisation), filtering them out of water (rhizofiltration), or breaking down organic pollutants (phytodegradation).

Table 1. Main phytoremediation mechanisms and their link to biomass use

Mechanism	What the plant does	Typical target	Fate of biomass
Phytoextraction	Absorbs metals and stores them in shoots	Cd, Pb, Zn, Ni, As in soil	Harvested; needs safe processing
Phytostabilisation	Immobilises metals in roots and soil	Mine tailings, degraded land	Often left in place; limited harvest
Rhizofiltration	Roots absorb or adsorb metals from water	Wastewater, wetlands	Harvested aquatic biomass
Phytodegradation	Plant enzymes and root microbes break down organics	Pesticides, hydrocarbons	Usually low contamination
Phytovolatilisation	Converts pollutants and releases them as vapour	Selenium, mercury	Little biomass issue

Source: General phytoremediation literature and Wijekoon et al. (2025).

A good cleaning plant has to survive on harsh, heavily polluted ground and still produce plenty of biomass (Ionata et al., 2024). The second trait is what makes a link with biorefining so attractive. Land that is not used for food can grow plants that clean the soil and also earn money (Wijekoon, 2025), which sidesteps the food-versus-fuel argument and keeps polluted soil out of the food chain.

The hidden treasure: bioactive compounds in plants

Plants produce a wide range of bioactive compounds, including alkaloids, flavonoids, terpenoids, and polyphenols, which have therapeutic and antioxidant value (Asiminicesei et al., 2024). Many of these compounds are secondary metabolites, which plants produce for defence and survival rather than for growth. This is where the story gets interesting, because metal stress and plant chemistry are closely linked. Exposure to heavy metals makes plants produce reactive oxygen species, and the resulting oxidative stress sets off signalling pathways that can change the metabolites the plant produces (Pandey et al., 2023; Asgari Lajayer et al., 2017). Phenolics, flavonoids, and carotenoids help the plant mop up these reactive molecules and bind metals (Asgari Lajayer et al., 2017). Therefore, in some species, moderate metal stress can act as an elicitor that increases the yield of valuable compounds. The effect is not always positive. Metals can increase or decrease the production of secondary metabolites, and the mechanism behind this is not yet clear (Pandey et al., 2023). For example, the root exudates of the wetland plant *Cyperus alternifolius* contained fewer phytochemicals as the metal concentration increased (Usharani & Vasudevan, 2017). Therefore, plant choice, metal dose, and harvest time must be carefully tuned. One reassuring point is that some medicinal and aromatic plants can accumulate metals in their foliage and can still be used to clean polluted sites without contaminating their essential oils (Asgari Lajayer et al., 2017). Because oils are separated by distillation, aromatic crops are considered strong candidates for this approach.

The biorefinery step: a cascade of products

A biorefinery considers the harvested plant as a source of many products rather than a single waste stream. For contaminated biomass, the guiding idea is a **cascade**: take out the high-value, metal-free products first, convert the residue next, and deal with the metals at the end (Figure 1). Gentle extraction recovers oils, polyphenols, and other bioactive compounds. Leftover biomass can be subjected to anaerobic digestion to produce biogas, as shown for plants grown to treat livestock wastewater (Hejna et al., 2021; Table 2). It can also be converted into biochar, an option that has been highlighted for treating municipal waste leachate and managing landfills in developing economies (W. Wijekoon, 2025). Finally, ash or residues rich in metals can be treated to recover the metals, which supports the goal of clean fuel production with minimal waste and no secondary pollution (Ionata et al., 2024).

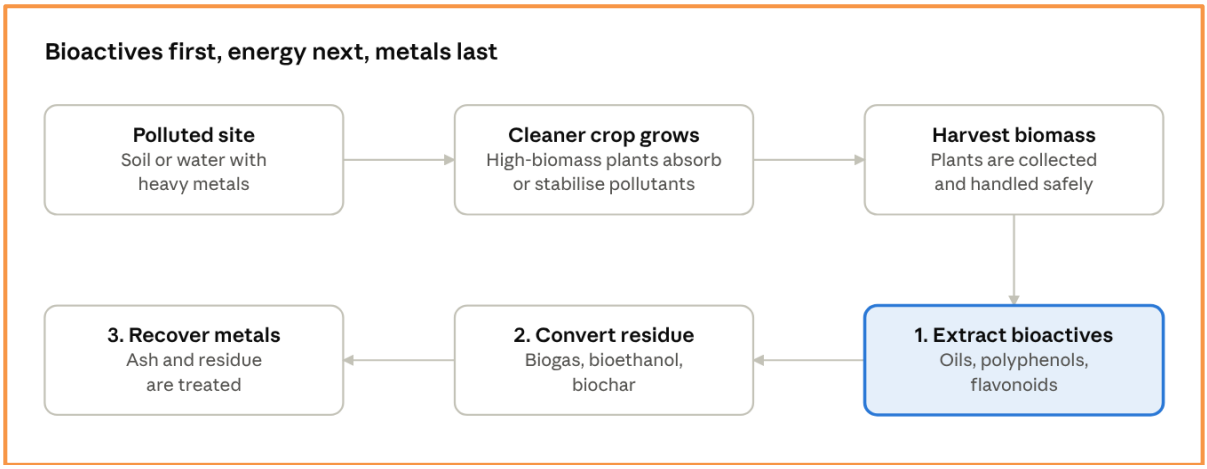

Figure 1. Integrated phytoremediation and biorefinery cascades.
The flow runs from the polluted site to harvest, and then through three refining steps.

Table 2. Biorefinery routes for plant biomass from phytoremediation

Step	Process	Main product	Key advantage	Key caution
1	Solvent or steam extraction	Essential oils, polyphenols, flavonoids	High value, small volume	Check metal residues in extract
2	Anaerobic digestion	Biogas (methane)	Renewable energy, digestate	Metals may end up in digestate
3	Fermentation	Bioethanol	Liquid fuel from cellulose	Needs pretreatment
4	Pyrolysis or torrefaction	Biochar, bio-oil	Sorbent and soil conditioner	Metals concentrate in char
5	Ash treatment	Recovered metals	Closes the loop, reduces waste	Cost and technology

Source: Hejna et al. (2021), Wijekoon et al. (2021), and Wijekoon et al. (2025).

Benefits for people and the planet

The combined system supports several UN Sustainable Development Goals. Pairing phytoremediation with bioenergy contributes to affordable and clean energy (SDG 7) and sustainable cities and communities (SDG 11) (W. Wijekoon, 2025). Beyond energy, it can restore degraded land and provide rural communities with new income from marginal fields. For agricultural extension workers, the message is practical: polluted land need not be abandoned, and farmers can be guided towards non-food crops that have real market value.

Challenges and the way forward

Several hurdles remain. Safe handling of contaminated biomass, sustainability concerns, and gaps in research remain open issues (W. Wijekoon, 2025). Phytoremediation is also limited by contaminant specificity, long timescales, and external conditions, such as climate (P. Wijekoon & Wickramasinghe, 2021). Finally, because metals can change the quality of medicinal plants, health risk assessment and compliance with international limits for plant-based products are essential before any extract reaches consumers (Asgari Lajayer et al., 2017).

Table 3. Key challenges and possible solutions

Challenge	Possible solution
Metals present in the final extract	Plant selection, metal testing of every batch, purification steps
Slow cleaning rate	High-biomass, metal-tolerant crops; soil amendments; root-zone microbes

Variable bioactive yield under stress	Optimise metal dose and harvest time; field trials
Safe disposal of metal-rich residues	Ash treatment, metal recovery, regulated landfill
High cost and lack of field data	Life cycle and techno-economic analysis; pilot demonstrations

Source: Wijekoon et al. (2025), Asgari Lajayer et al. (2017) and Kowalska and Biczak (2025).

Conclusion

Combining phytoremediation with biorefining changes the perception of polluted land. Contaminated biomass is no longer a burden: bioactive compounds are extracted first, the residue is converted into energy and materials, and metals are recovered at the end, leaving very little waste. Plants growing under stress may even produce more of certain valuable metabolites, although excessive metal content can lower quality; therefore, careful crop choice and monitoring are vital. Questions of safety, cost, and regulation remain, and they call for field-scale trials, life cycle assessment, and clear standards. Once these are in place, the approach can deliver clean soil, renewable energy, valuable plant products, and extra income for farmers, representing a genuine example of circular and sustainable agriculture.

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