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Waste Management: New Solutions in Recycling and Waste-To-Energy Technologies

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Abstract— Weeds, often seen as ecological threats, can be transformed into valuable bio-resources through a sustainable waste-to-wealth approach. Traditional weed control methods are costly and inconsistent, highlighting the need for integrated solutions. Weeds offer significant potential for composting, bioenergy production, material recycling, and phytoremediation. Their use in soil amendments enhances fertility and carbon sequestration. Due to their abundance and low cost, they are ideal for generating charcoal, biofuels, and other renewable energy sources. Reimagining weeds as assets supports environmental conservation, sustainable agriculture, and the circular economy, turning a widespread nuisance into an opportunity for ecological and economic gain.

Keywords— Weed; sustainable; environment; productivity; ecosystem

I. INTRODUCTION

Weeds are plants that are considered unwanted in specific environments due to their potentially harmful and economically detrimental effects. They can severely impact biodiversity and primary production, contributing to environmental degradation, reduced farm and forest productivity, and the displacement of native species [1,2]. Weeds are the biggest biological threat to agricultural production systems, damaging cropped and uncropped land, when it comes to farming, these plants reduce the quality of pastures and agricultural products by competing with crop plants for limited resources, additionally, they hinder irrigation once they have grown enormously. Several of these weed plants are toxic, raise production costs, and attract pests [3,4]. Weeds are generally considered harmful pests as they adversely affect crop productivity and cause health problems in humans and animals when infest field crops [5]. Weed control with herbicides is the miracle of modern agricultural science. However, we are being confronted with herbicide resistance evolution in weeds and persistent concerns about contamination of crop produce due to the long-term use of herbicides, particularly in vegetables. To date 272 herbicide resistant weed species have been found in 100 crops in 72 countries worldwide [6]. Studies in recent years have revealed that chemical weed control has many hazards including environmental damage, food toxicity in weeds and weed resistance [7-10]. Therefore, identification and implementation of alternative weed management strategies are crucial for better productivity and sustainability of agroecosystem.

Proper utilization of weeds as value-added products can enhance the income of farmers, an added benefit to control efforts in various agroecosystems. Weed may have beneficial uses such as manure, compost, soil and water conservation resources, etc. (Fig.1).

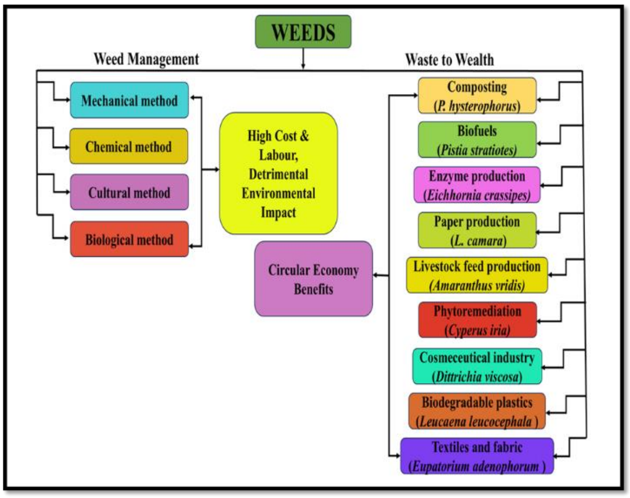

Fig.1. Sustainable approach to weed management by converting weeds into useful products

Moreover, many weed species have medicinal properties and could be developed into medicinal products that provide additional income to farmers [11]. With proper attention and planning, identification of medicinal properties of weedy herbaceous plants and their commercialization could be a

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highly lucrative venture [12, 13]. This would also make some natural medicines available and affordable to the public [11]. Weed management is a critical aspect of agricultural and environmental sustainability, as invasive plant species compete with crops, reduce biodiversity, and disrupt ecosystems. Traditional methods, such as chemical herbicides and mechanical removal, are increasingly scrutinized due to their environmental toxicity, herbicide resistance, and contribution to soil degradation. In response, innovative solutions are emerging that align with circular economy principles, focusing on recycling weeds into valuable resources or converting them into energy.

Weed biomass can be used as compost for organic crop production. Weed compost has high nutrient contents and the use of weed compost has resulted in increased growth and development of different crop plants [14,15]. Weed may also be used as a source of hay and silage because many weedy plants are rich in nutrients, with higher palatability and digestibility than common forages [16,17]. Many weedy plants are allelopathic, gaining dominance over other weed by producing phytotoxic compounds can become major source of forage for animals in rangelands and pastures [18,19]. Bioherbicides with less environmental impact can be produced from such plants. Previously, some weed plants such as *Miscanthus* spp. and *Arundo* spp. have been explored as feedstock for renewable biofuel [20-24]. Weed can also be used in biochar preparation [25], dye degradation, paper making and cellulose production [26], corrosion inhibition [27], source of dye [28], bioadsorption [29] and phytoextraction [30]. This chapter discusses the utilization of weedy plants as value-added products and explores advancements in weed recycling (e.g., composting, mulching) and weed-to-energy technologies (e.g., anaerobic digestion, pyrolysis, bioethanol production), highlighting their environmental, economic, and social benefits.

Circular economy is viewed as a solution for fostering a sustainable system [31] and aims at the elimination of waste [32]. Thus, circular economy can be defined as the transition from a linear model, where resources are transformed, used, and discarded, to a circular (regenerative) model in which materials are reused whenever possible [33]. Circular Economy solutions are aligned with the United Nations Sustainable Development Goals requiring transformation of the current business practices [34].

Weeds as composting material

Weed biomass can be composted in pits or heaps under aerobic or anaerobic conditions [35]. Composts derived from weeds exhibit nutrient contents that are equal to or exceed those of cow dung, farmyard manure (FYM), and green manure crops such as sun hemp (*Crotalaria juncea* L.) and fast stick (*Gliricidia maculata* Jacq.), with a significant decrease in the carbon to nitrogen ratio [36]. However, the quality of compost that is produced by weeds varies depending on the species of weeds and whether they are used exclusively or in combination with other materials. Higher NPK values in compost obtained from a combination of *Parthenium hysterophorus* L. and *Echinochloa colona* (L.) compost compared to individual weed compost [37]. The nutrient supply capacity of weed compost is dependent upon the composting process. Nutrient levels in weed compost produced with earthworms under aerobic circumstances were better compared to those in compost generated under anaerobic conditions.

Vermicomposting method utilises earthworms to recycle non-toxic organic waste into the soil. Succulent weeds can be utilised for vermicomposting to supplement farmyard manure and inorganic fertilisers [36]. The quality of vermicompost is dependent upon the species of earthworms utilised. Compost recovery and overall nutrient content were greatest in *Ipomoea carnea*, followed by *Mikania micrantha* (Kunth.) and *P. hysterophorus*, with *Eudrilus* earthworm identified as the most rapid decomposer [38]. Babu et al. (2008) indicated that many troublesome weeds, including *Lantana camara*, *Saccharum munja*, and *Eichhornia crassipes*, can serve as effective sources of vermicompost [39]. However, the shortage of traditional organic fertilisers, such as animal waste, compels the utilisation of alternative organic manure sources, including weed compost and green manuring. Composts derived from weeds exhibited a superior nutritional content and a reduced carbon to nitrogen ratio compared to composts produced from crops straw [40]. The basal application of compost obtained from weeds, when combined with either the recommended or a reduced dosage of inorganic NPK, has been reported to enhance the soil's available NPK, resulting in a significant accumulation of nutrients by the end of the crop season, compared to the soil's initial nutrient status [41,42]. The utilisation of the full recommended dosage of inorganic fertiliser combined with *Chromolaena odorata / P. hysterophorus*/*Eleusine coracana* compost at 2.6 t ha-1 produced maize kernel yields comparable to those achieved with the 100% recommended dosage of inorganic fertiliser plus 10 t ha-1 of farmyard manure (FYM) [43]. This allows us to conclude that the bio-management of weeds as a compost source is an exemplary strategy to improve crop yield and enhance soil fertility potential.

Weeds in paper making

Diverse weed species provide as a substantial source of lignocellulosic biomass. The concentrations of lignin, hemicelluloses, and cellulose in 77 weed species, revealing that certain species had up to 20% lignin, 32% hemicelluloses, and 56% cellulose [44]. The concentrations of lignocellulosic materials exceed those seen in oat, barley, maize, and rye straw [45]. Consequently, weeds can serve as a low-cost and readily accessible raw material for the manufacturing of several grades of paper, possessing suitable strength and quality for various commercial applications [46]. *L. camara* had significant physical strength across various NaOH concentrations, indicating that Lantana fibre may be effectively utilised in paper production [47]. The chemical characteristics of three weed species, including *Merremia peltata* (L.) Merr., *Amaranthus viridis*, and *Andropogon saccharoides* var. erianthoides Hack., were examined for their potential usage in papermaking. The results indicated that the holocellulose and lignin contents of these weeds were comparable to those found in wooden trees [48].

Weeds as biosorbent

Biosorbents derived from the stems of *Diplotaxis harra* and *Glebionis coronaria* effectively eliminated Cd(II) ions [49]. This investigation revealed that pH levels ranging from 6.5 to 7.5 achieved the highest adsorption of 18.31 mg/g at 25 °C. Among inorganic ions, Al3+ exhibited the most potent inhibition owing to its significant affinity for Cd(II) ions. They suggested that functional groups on the surfaces of *D. harra* and *G. coronaria* may be responsible for Cd(II) biosorption. *Ageratina adenophora*, a weed, has been investigated as a possible and cost-effective biosorbent for the removal of copper from aqueous solutions [50]. *Cyanthilium cinereum* and *Paspalum maritimum* were investigated as possible biosorbents for methylene blue dye in effluents [51]. *Salvinia minima* has also been investigated as an efficient natural absorbent for the removal of dyes and heavy metals from wastewater [52]. Heavy metals (cadmium, chromium, lead, and zinc) may be naturally removed from water by two weed species, *Lotus corniculatus* and *A. viridis* [53]. Recent research showed a promising trend for the biosorbent ability of weeds. Weed-based biosorbents provide significant promise for the efficient removal of heavy metals from wastewater. Cost research indicated that weed-based biosorbents are more economically viable than traditional adsorbents, such as activated carbon [54].

Weeds for phytoextraction

Phytoextraction is an environmentally acceptable, cost-efficient, and rapidly developing method for the removal of heavy metals from soil. Weeds demonstrated significant potential for phytoextraction, efficiently eliminating contaminants from soil. Multiple weed species (Table I), such as *Jatropha curcas, Trianthema portulacastrum, Cynodon dactylon, Typha angustifolia, Phyllanthus reticulatus, Echinochloa colonum, Vetiveria nemoralis, and Eleusine indica*, demonstrated significant efficacy in the extraction of various heavy metals, including cadmium, chromium, lead, and mercury from soil [55]. *C. procera*, a common weed, shown significant potential for growth in polluted soil and the remediation of arsenic (As) from arsenic-contaminated soil [56]. The removal of heavy metals occurs through absorption in both underground and aerial parts.

TABLE I. Weeds as metal hyper accumulators

Weed plants	Accumulation part	Metal	References
Bidens pilosa	Whole plant (stems, leaves and shoots)	Cd	[57]
Amaranthus virdis	Root	Cd	[57]
Solanum nigrum	Stem	Cd	[58]
Chromolaena odorata	Stem and leaves	Zn	[59]
Eichhornia crassipes	Leaf	Cr	[60]
Taxacum mongolicum	Shoot	Cd	[60]
C. album	Root and Shoot	Zn, Cd, Pb, Cu	[61]
Trifolium pratense	Root	Cu	[63]
Euphorbia hirta	Root	Cr, Cu, Ni, Pb, Cd	[62]
Rumex acetosa	Leaves	Cu	[63]
R. globosa	Root and Shoot	Cd, Pb, Cu, Zn	[61]
Lolium multiflorum	Leaves	Zn	[63]
Parthenium hysterophorus	Shoot	Ni, Cd, Pb, Cr, Cu	[62]
Rorippa globosa	Stem and leaves	Cd	[61]
Bidens frondosa	Shoot	Cd	[57]
Leersia hexandra	Dry leaf matter	Cr	[64]
Phargmites australis	Rhizome	Cr	[65]
Sedum alfredii	Zn	Leaves	[66]
Potentilla griffithii	Zn	Leaves	[67]
Lantana camara	Pb	Leaves	[68]

Weeds as a source of forage and silage

Weeds consistently grow across agricultural area, covering crop fields, orchards, roadways, and pastures. Therefore, it is crucial to understand the nutritional potential of various plant species prior to making decisions regarding management about weed control. The significance of weeds as silage has not gotten much attention since in the past it was thought that they had little nutritional value and were inedible to the majority of animal species. In India, Pakistan, Sri Lanka, Bangladesh, and several other developing nations, animals consume a wide variety of weeds as fodder, including grasses (*Echinochloa crus-galli* L., *Bromus tectorum* L., *Hordeum jubatum* L., *Setaria viridis* L.) and broad-leaved plants (*Chenopodium album* L., *Descurainia sophia* L., *Amaranthus retroflexus* L., *Convolvulus arvensis* L., *Rumex crispus* L.) [69]. Poor landless farmers who lack sufficient land to grow feed for their animals may also benefit from weeds. Weeds' nutritional content has a significant role in determining the quality of their silage. Certain weeds, for instance, are poisonous for cattle feed because they contain harmful compounds. *Conium maculatum* L., *Cicuta maculate* L., *Pteridium aquilinum* L., *Triglochin palustris* L., *Equisetum arvense* L., *Phytolacca americana* L., *Caltha palustris* L., and *Helenium automnale* L. are common toxic weeds that are found in pastures and fodder crops [70, 71]. However, a lot of weed species offer the best nutritional content for feed for animals. The invasive weed *Alternanthera philoxeroides* was found to contain nutrients similar to those found in common fodder crops [72]. These nutrients included iron (34.4–64.5 mg kg1), zinc (15.1–29.8%), manganese (2.3–3.6%), acid detergent fibre (13.0–17.9%), neutral detergent fibre (23.3–38.9%), and crude protein contents (10.2–14.2%), which ranged 13.0–17.9, 23.3–38.9, and 10.2–14.2%, respectively. After investigating the nutritional composition of 14 local weed species, Gutierrez et al. (2008) came to the conclusion that the mineral concentrations in the weeds were suitable for consumption by cattle [73]. Furthermore, the majority of weeds have the ideal amount of crude fibre and protein for healthy growth of animals.

Weed as a source of biochar

Invasive plant biomass may be converted into solid biofuel, such as biochar or hydrochar. Biochar is a versatile substance with several potential applications; initially, it can serve as a solid fuel, since the pyrolysis process eliminates concentrations of other elements, resulting in carbon as the major component of its composition. Consequently, biochar's highest heating value can attain up to 40 MJ/kg, whereas the highest heating value (HHV) of invasive plant biomass is less than 20 MJ/kg [74]. Biochar derived from invasive plants can serve as sorbents for the removal of contaminants, such as trace metals from effluent, in along with serving as fuel [75]. One potential application of biochar is in agriculture. Biochar has been shown to have long-term and beneficial implications as a sustainable soil amendment. It enhances the soil environment, increases water retention capacity, stabilises pH, supports the slow release of nutrients, and reduces the bioavailability of pollutants, such as heavy metals, as well as greenhouse gas emissions [76, 77]. The utilisation of invasive plant biomass as a feedstock for biochar production, effectively showing the advantages of this method for the safe management of plants, while also highlighting the potential to produce chars with significant variations in structure, composition, and enhanced adsorption capacities [78, 79]. The key advantage of invasive biomass utilisation through pyrolysis to generate biochar is its remarkable safety. The utilisation of existing facilities might be possible for the production of biochar. This technology has been employed since ancient times to manufacture wooden biochar, and it can be readily upscaled and modified to process other types of biomasses.

Weeds as a source of biofuel

Liquid and gaseous biofuels derived from invasive plants outperform solid biofuels in terms of application adaptability. Invasive plant biomass can be converted into liquid or gaseous biofuels by thermochemical or biochemical processes. Biochemical processing involves isolating oil components from plant biomass or hydrolysing polymeric carbohydrates like cellulose, hemicellulose, and starch. The desired biofuel is then isolated after fermentation. Depending on the type of biomass, pretreatment methods, and subsequent processing, it is possible to obtain hydrocarbons ranging from methane to high molecular condensed polyaromatics (tars), lower alcohols (methanol, methanol, butanol, and others), hydrogen, and other substances that can be used for energy production and other purposes [80, 81]. The feasibility of converting invasive plant biomass into liquid or gaseous biofuels has been demonstrated in many cases. Fast pyrolysis of Eastern redcedar (*Juniperus virginiana*) has effectively yielded gasoline and diesel, with production costs and potential prices for products suggesting that the conversion of invasive biomass into biofuel is financially feasible [82]. The feasibility of converting invasive plant biomass into liquid or gaseous biofuels has been demonstrated in many cases. Fast pyrolysis of Eastern redcedar (*J. virginiana*) has effectively yielded gasoline and diesel, with production costs and potential prices for products suggesting that the conversion of invasive biomass into biofuel is cost-effective [82]. The production of biofuel from aquatic plants such as water fern, water lettuce, and duckweed represent a less concentrated energy source. Utilising sustainable techniques to generate biofuel from aquatic vegetation can transform the cost of eradicating invasive aquatic species into a profitable investment [83]. The safe utilisation of invasive plant biomass is considered as a method for restoring ecosystem services. A wide range of aquatic invasive plants, such as *Phalaris arundinacea*, *Phragmites australis*, and *Typha*, significantly disrupt ecosystem services. Their removal can aid in the restoration of natural habitats, enhance biological diversity, and contribute to the reversal of eutrophication. Invasive species prevalent in Europe, such as *Reynoutria japonica*, *Heracleum mantegazzianum*, *Impatiens glandulifera*, and *Solidago gigantea*, were utilised for biogas production. The anaerobic digestion process yielded a methane concentration of 50%, aligning closely with the typical range observed in commonly utilised biomass, which falls between 48% and 65% for energy crops. The non-catalytic and catalytic pyrolysis of the invasive *Pennisetum purpureum* grass resulted in the production of biochar, bio-oil, and syngas [84].

Weeds as a source of biologically active substances

The processing of plant biomass plays a significant role in sustainable management, as it reveals biologically active and nutritionally valuable substances present in many invasive plants. Numerous investigations have shown that various invasive plants possess considerable nutritional value and hold significant promise for the recovery of biologically active compounds found in their composition [85]. Polyphenols represent the most thoroughly studied category of compounds in invasive plants [85]. Polyphenol isolation extraction has utilised lower aqueous alcohols such as methanol and ethanol, along with acetone and similar solvents. Additionally, acidification of these solvents has frequently been employed to stabilise the structures of polyphenols [86]. Various extraction techniques have been used to investigate polyphenols from invasive plants. In addition to conventional solvent-based extraction, innovative methods such as supercritical carbon dioxide extraction and pressurised liquid extraction have been used to isolate polyphenolics (10 phenolics identified) and lipids from *Solidago virgaurea* [87]. Extraction of flavonoids and phenolic acids from *Solidago canadensis* and *Solidago gigantea* utilising ethanol, methanol, acetone, water, and combinations of organic solvents. Chlorogenic acid, rutin, hyperoside, and glycosides of isoquercetin, kaempferol, isorhamnetin, and quercetin were identified in the extracts [88]. Invasive plants may provide as a valuable source of biologically active compounds with potential applications in medicine, pharmacology, veterinary medicine, dietary supplements, and other domains. Phenolic acids and flavonoids, including sinapic acid and ferulic acid, were isolated from biowaste generated during the eradication of *Tradescantia fluminensis* [89]. Alkaloids represent a significant category of biologically active compounds, commonly involved in the defence mechanisms of plants against predators and infections. A variety of invasive plants are known to possess higher concentrations of alkaloids, with Lupin species serving as a notable example of the importance of this category of compounds [90, 91]. Certain species of weed plants are known to produce essential oils. For instance, L. camara leaf contains 0.4% essential oil, while the aerial parts of *Eupatorium adenophorum* have 0.56%. *Ageratum conyzoides* shows a content of 0.3% in its aerial parts, and *Sphagneticola trilobata* ranges from 0.18% to 0.25%. *Cannabis sativa* has 0.1%, *Artemisia annua* contains 0.5%, and *Cyperus rotundus* tubers exhibit a range of 0.4% to 0.6% essential oil content. The applications of those oils extend to the flavour, fragrance, cosmetic, and pharmaceutical sectors.

Weeds as herbal medicines and pharmaceuticals

In addition to essential oils and aroma chemicals, certain weeds generate secondary metabolites that hold aromatic and medicinal importance, including alkaloids, terpenoids, and cardiac glycosides. Numerous weed species serve as abundant sources of various natural compounds and have been widely utilised in traditional health care systems such as Ayurveda, Unani, and Siddha (Table II). The *Chenopodium album*, a winter season weed often referred to as bathua in Hindi, is recognised for its potential to alleviate joint pain caused by uric acid accumulation. It is frequently utilised as a blood purifier and sedative. Pharmaceutical studies have indicated that this plant exhibits anthelmintic, sperm immobilising, and contraceptive properties. *Marsilea quadrifolia*, a weed of the kharif season, thrives in submerged soil or moist environments. Commonly referred to as sushni, it is utilised as a vegetable for the treatment of insomnia. *Phyllanthus niruri*, a common weed in agricultural fields, possesses a broad spectrum of medicinal properties and is utilised worldwide. In India, approximately 120 species of weeds serve as the raw materials for the pharmaceutical industries Therefore, it is essential to create an appropriate marketing network that allows ordinary farmers to generate extra income through the collection of weeds from their fields [92].

TABLE II. Bioactive compounds from weeds are used in drug development

Weed Species	Drug/bioactive compound	Diseases cured	References
Datura metel L.	Scopolamine	Prevention of motion sickness, As palliative in Parkinson's disease	[93, 94]
Glycyrrhiza glabra L.	Glycyrrhizin	Treatment of chronic hepatitis C, Anticariogenic activity	[95, 96]
Cytisus scoparius (L.) Link	Sparteine	Use in obstetrics	[97]
Artemisia annua L.	Artemisinin	Malaria	[98]
Ammi visnaga (L.) Lam.	Khellin	Kidney stones, prevention of stone formation associated with hyperoxaluria, nephrolithiasis, anginal syndrome	[99]
Atropa belladonna L.	Atropine	Myopia, Sinus bradycardia, acute myocardial infarction	[100, 101]
Papaver somniferum L.	Papaverine	Use in acute arterial occlusions, use in cerebral angiospasm (vascular encephalopathy)	[102]
Vinca minor L.	Vincamine	Treatment of primary degenerative and vascular dementia, anti-depressive	[103]
Digitalis purpurea L.	Digitoxin	Anticancer agent	[104]
Berberis vulgaris L.	Berberine	Giardiasis, Central Nervous System, Polycystic ovary syndrome	[105]
Lobelia inflata L.	Lobeline	Treatment of psychostimulant abuse	[106]
Hyoscamus niger L.	Hyoscyamine	Hallucinogen	[107]
Brassica nigra L.	Allyl isothiocynate	Antimicrobial activity	[108]
Silybum marianum (L.) Gaertn.	Silymarin	Liver diseases; Prevention of alloxan-induced diabetes mellitus in the rat	[109]
Colchicum autumnale L.	Colchiceine, Demecolcine	Treatment of gout, treatment against acute liver damage	[110]
Catharanthus roseus L	Vinblastine, Vincristine	Anticancer agents	[111]
Anabasis aphylla L.	Anabasine	Inhibition of aromatase in human trophoblast, toxicity to culicine mosquito larvae	[112]

Weeds as a source of bio-herbicides

Due to the rapidly growing resistance to all major herbicide groups, there is an urgent need for herbicides with novel mechanisms of action. Additionally, the lack of natural pesticides makes controlling weeds in organic farming systems extremely difficult. Numerous weed species are gaining significance as possible agents for weed management due to their diverse phytotoxic chemicals. These phytotoxic chemicals can impede the germination and growth of several weed species, even those that have developed resistance to herbicides. Various weed species, including *C. album*, *Medicago denticulata, Melilotus indica, Convolvulus arvensis, Vicia hirsuta*, *Lathyrus aphaca*, and *R. acetosella*, shown significant herbicidal potential against *P. minor* [113]. Honey weed (*Leonurus sibiricus* L.) contains various phytotoxic compounds that exhibit an inhibiting impact on rice, wheat, and mustard [114]. The aqueous extract of *Conyza canadensis* L. had a significant inhibitory impact on numerous crops, due to the presence of diverse phenolic compounds, including gallic acid, syringic acid, catechol, and vanillic acid [115]. The pronounced inhibitory impact of various plant parts of *P. hysterophorus* on the germination and development of many crops was related to the phenolic acids present in this weed [116]. The predominant phytotoxic chemicals identified in weeds include alkaloids, fatty acids, phenolics, terpenoids, indoles, lignans, cyanogenins, flavonoids, and coumarins. Moreover, allelopathic compounds released by aquatic weeds exhibited an increased phytotoxic response towards diverse terrestrial weeds and crop species [118] as flora within a specific ecosystem may be more adapted to the allelochemicals than those from different ecosystems [117, 119]. Consequently, phytotoxic substances emitted by aquatic weeds can be identified and utilised as prospective bio-herbicides. Moreover, these phytotoxins may enhance the development of agricultural plants at low concentrations [119]. The application of chemical herbicides is not a viable method for crop production due to the rapidly increasing issue of herbicide resistance in weeds and the environmental risks associated with herbicides. Therefore, using weeds to produce bio-herbicides provides an environmentally friendly alternative for sustainable weed management in agricultural practices.

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