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Exploring the Potential of Allelopathy of *Parthenium hysterophorus* in Ecological Agriculture

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Abstract *Parthenium hysterophorus*, an invasive and ecologically harmful weed, produces allelopathic chemicals including phenolics and sesquiterpene lactones that impact surrounding vegetation. These chemicals can serve as natural growth regulators, herbicides, and antimicrobial agents, presenting an alternative to synthetic pesticides. The use of *P.hysterophorus* in ecological agriculture, particularly in crop rotation, intercropping, and as a green manure or compost, has shown promise in improving soil health, fertility, and plant growth. *Parthenium*-derived compost enhances seed germination, root development, and nutrient content, while increasing organic matter and soil porosity. Additionally, the plant's biomass can sequester carbon and reduce greenhouse gas emissions, including CO_2 and N_2O. Despite its potential benefits, the use of *P.hysterophorus* compost remains underutilized due to limited adoption by farmers. Innovative composting methods and the development of biopesticides could facilitate more widespread use, turning this harmful weed into a valuable resource for sustainable agriculture. Further research and awareness are essential to fully harness the allelopathic properties of this plant in agricultural systems.

Keywords: Allelopathy; Compost; Ecological agriculture; *Parthenium hysterophorus*; Plant pathogen inhibition; Soil fertility

Introduction

Application of allelopathy in agricultural production

Plant allelopathy is a form of nutritional interaction between donor and receptor plants, which can exert either positive or negative effects. Positive effects include agricultural benefits such as weed control, crop protection, and crop reestablishment, while negative effects may lead to autotoxicity, soil sickness, or biological invasion. Allelochemicals produced by donor plants influence the growth and development of receptor plants, prompting the receiver plants to respond by altering gene expression. (He et al., 2012). The use of synthetic insecticides, herbicides, fungicides, and other pesticides has significantly disrupted the ecology of biotic communities in both agricultural and natural ecosystems, ultimately disturbing the ecological balance within food chains. In contrast, natural plant-derived products, such as allelochemicals, are secondary metabolites that play a crucial role in ecological interactions and offer a promising alternative source of agrochemicals. Allelochemicals can serve as growth regulators, herbicides, insecticides, and antimicrobial agents for crop protection. Bioherbicides, in particular, present a viable substitute for synthetic herbicides and costly mechanical methods used in agricultural practices, as they do not leave residual or toxic effects. However, the efficacy and specificity of many allelochemicals are limited, which warrants further research and development (Bhadoria, 2011). To ensure the sustainable development of agriculture, it is essential to explore cultivation systems that leverage the stimulatory or inhibitory effects of allelopathic plants to regulate plant growth and development while minimizing the risk of allelopathic autotoxicity.

The use of allelopathic crops in agriculture is increasingly being recognized as a valuable component of crop rotation, intercropping, cover cropping, green manure, and mulching systems. One of the main challenges in transitioning from conventional to organic farming systems is effective weed control in agroecosystems (Barberi, 2002). The commonly used methods of weed control include herbicide application, mechanical weeding, and hand weeding. However, these methods have several drawbacks, including the evolution of herbicide resistance, negative environmental impacts, risks to human and animal health, high costs, soil structure degradation, and significant labor requirements. Combining multiple weed control methods has been shown to be effective in reducing the likelihood of herbicide resistance development in weeds (Cheng et al., 2015). Non-chemical methods of weed control are preferred in ecological agriculture. Among these, allelopathic suppression of weeds through the use of allelopathic plants in crop rotation and phytotoxic mulches for soil fertility management has proven to be highly effective. Utilizing allelopathic plants as ground cover provides an environmentally friendly option for weed management, reducing the negative environmental impacts of conventional agricultural practices. The allelochemicals released from decomposed mulch can suppress weed growth, lower pest and disease incidence, and improve soil organic matter content, ultimately enhancing soil fertility. This allelopathic exclusion occurs because allelochemicals negatively impact seed germination by inhibiting the hydrolysis of reserve food, cell division, and other critical physiological processes (Rice, 1974). Allelochemicals can be used as weedicides at higher concentrations and germination enhancers at lower concentrations (Ebrahimi et al., 2016; Dhyani et al., 2017).

Nitrification of nitrogen fertilizers is a major contributor to nitrogen enrichment in soil through leaching. Nitrification-inhibiting substances, which are allelochemicals produced by plants, are an ideal choice for managing soil nitrification. These allelochemicals act on soil microbes to inhibit biological nitrification, thereby reducing N_2O emissions, improving nitrogen fertilizer utilization, and minimizing environmental pollution (Dietz et al., 2013). Additionally, crop allelopathy can be effectively used to control weeds and insects in the field, helping to combat insect resistance and reduce reliance on chemical pesticides, thereby mitigating environmental pollution. However, a challenge with some allelochemicals is their high degradability in soil (Bhadoria, 2011; Ihsan et al., 2015). To enhance their effectiveness in inhibiting weed growth, these allelochemicals can be formulated as wettable powders. Additionally, organic herbicides or plant growth inhibitors derived from allelopathic plant materials have been developed to suppress weed growth in the field. Allelopathy can be harnessed to increase crop production by avoiding negative impacts, exploiting stimulating effects, developing allelopathic crops, and using allelochemicals as pesticides and growth regulators

Allelopathic Parthenium hysterophorus and its use in agriculture

Parthenium hysterophorus is a noxious invasive weed of global significance, responsible for severe human and animal health issues. Found in both natural and agroecosystems, its invasion has led to significant biodiversity loss (Kumar et al., 1999), often causing habitat alteration or complete replacement. In agricultural ecosystems, *Parthenium* competes directly with crops for space, nutrients, water, and sunlight, and indirectly through allelochemicals, particularly phenolics and sesquiterpene lactones, mainly parthenin. Parthenin is rapidly degraded, with an average half-life (DT50) of 59 hours (Belz et al., 2009).

The reduction in pasture yield and agricultural productivity can be attributed to various factors, including allelopathic inhibition, contamination of grains and seeds, reduced nodulation in leguminous plants, and serving as an alternate host for plant viruses and insect pests (Gnanavel et al., 2013). Despite its harmful effects, *Parthenium* also has environmental applications and pharmacological activities, including chemotherapeutic actions. The beneficial and harmful effects of *Parthenium hysterophorus* are due to its chemical constituents. All parts of the plant including hairs, trichomes, pollen, and fruits contain several secondary metabolites, such as alkaloids, flavonoids, and phenolics (Javaid et al., 2010). The concentration of these secondary metabolites is highest in the leaves, followed by the inflorescence, fruits, roots, and stems (Kapoor, 2012). Allelochemicals with negative allelopathic effects are key components of the plant's defense mechanisms against weeds and herbivory. Phenolics and sesquiterpene lactones (primarily parthenin) are released into the surrounding soil through exudation or decaying processes, inhibiting germination and growth in a wide variety of agricultural crops, including both food and fodder plants (Navie et al., 1996). Phenolic compounds, known for their antioxidant properties, also serve as chelators of metal ions under heavy metal stress (Parvin et al., 2022).

A field experiment using extracts from shade-dried *Parthenium hysterophorus* leaves applied to *Brassica juncea* for controlling the mustard aphid (*Lipaphis erysimi*) demonstrated a reduction in initial infestation, likely due to the phenolic acids present in the leaves of this plant. *Parthenium hysterophorus* acts as a hyperaccumulator, aiding in the remediation of polluted or contaminated soils by removing toxic elements (Nithya et al., 2015). Furthermore, parthenin, a volatile compound found in *Parthenium hysterophorus,* exhibits both phytotoxic and insecticidal properties, and has been shown to control aphids and whiteflies in fields of potato and okra (Baig et al., 2022).

A marked increase in growth, seed germination, and metal tolerance against heavy metals has been observed with leachates from *Parthenium hysterophorus* plant parts. Flower leachates, which contain high amounts of auxin hormones, showed positive effects on seed germination in *Phaseolus mungo* and enhanced metal tolerance against Fe, Pb, Hg, and Ni (Lalitha et al., 2012). The extract was also found to be effective against brinjal fruit borer and pathogenic fungi in seeds. It has been reported that the effects of extracts from fresh and dried plant parts differ, with applications before plant emergence being more effective in promoting growth (Marwat et al., 2008). The use of allelopathic plant materials for mulching at 1-2 tons/ha has been shown to reduce weed biomass by 70% and increase rice yield by 20% in paddy fields (Xuan et al., 2005).

Allelopathic inhibition by water extracts of various *Parthenium hysterophorus* plant parts has been shown to affect economically important plant pathogens (Niranjan et al., 2024). *Parthenium* compost has been reported to reduce weed populations, likely due to the persistent allelopathic compounds in the plant debris even after composting (Son, 1995). The infestation of areas by *Parthenium* deteriorates soil quality, negatively affecting forage productivity by reducing pasture carrying capacity and agricultural output (Khosla et al., 1981).

Managing *Parthenium hysterophorus* is challenging due to its rapid proliferation and ecological adaptability. While many control measures have been implemented, none have proven entirely successful due to inherent limitations. Effective management strategies are essential to mitigate the threats *Parthenium hysterophorus* poses to biodiversity and economic stability. The autotoxic effects of water-soluble secondary metabolites, such as sesquiterpene lactones and phenolic acids, temporarily inhibit seed germination, with population regulation being influenced by the concentration of autotoxins in the environment (Picman et al., 1984). Leachates from *Parthenium hysterophorus* leaves are particularly toxic when applied to foliage, preventing rooting and sprouting of stem cuttings and reducing the regeneration potential of mature plants (Anita Kumari et al., 2017). Organic farming, which prioritizes the conservation of natural resources, biodiversity, and the earth's natural waste absorption capacity, contributes to sustainable agriculture. Composting is an economical and practical method for managing *Parthenium*, providing both nutrients and non-nutritive allelochemicals. *Parthenium hysterophorus* has significant potential in agriculture due to its ability to modify soil health and improve plant performance (Kishor et al., 2010).

Ecological role of allelopathic Parthenium

Allelochemicals play important ecological roles beyond weed suppression, including plant defense, nutrient chelation, and the regulation of soil biota, all of which influence decomposition and soil fertility. Composting, an allelopathy management practice, is commonly applied in agriculture. Organic farming relies on organic inputs that sustain ecological balance without harming the ecosystem. The addition of allelopathic *Parthenium* compost and crop residues as mulch enhances the physicochemical, biological, and nutritional quality of soil. Locally available, allelopathic *Parthenium* biomass, when used for composting and mulching, effectively sequesters carbon in the soil. *Parthenium* compost increases the organic matter content of soil, which improves overall pore space, reduces bulk density, and alleviates soil compaction. Mulching with *Parthenium* compost improves water infiltration, water retention, root penetration, and crop growth. Compost derived from *Parthenium hysterophorus* has significantly higher concentrations of micro (Fe, Zn, Mn, Cu) nutrients. According to the finding by Kishore et al., 2010, macro nutrient (N, P, K) content making it twice as nutrient-rich as farmyard manure macro nutrient values from the study by Sankaranarayanan et al., 2013– Table 1.

Table 1. Manurial value of *Parthenium* compost and Farm yard manure

Macro nutrients (%)	*Parthenium hysterophorus* compost (Kishore et al.,2010)	Farm yard manure (Sankaranarayanan et al., 2013)
Total N	1.58	0.5
Total P	0.38	0.2
Total K	1.64	0.5

A study investigating the effect of integrated *Parthenium* compost on wheat growth and yield revealed that the application of a full dose of nitrogen through composted *Parthenium* adversely affected the acquisition of both macro and micro nutrients and plant growth. This was attributed to the allelopathic effects of *Parthenium*, which interfered with metabolic processes in the plant. However, the maximum uptake of essential nutrients was achieved with the integrated use of 50% of the recommended nitrogen dose from both composted *Parthenium* and urea, in combination with the application of nitrogen-fixing *Azotobacter* (Kishor et al., 2010) – Table 2.

Table 2. Integrated use of *Parthenium* compost on macronutrient acquisition and grain yield of wheat (g/pot)

Treatment	Total macro nutrient acquisition(g/pot)				Grain yield (g/pot)
	N	P	K	S	
100 % urea (U)	0.43	0.10	0.49	0.12	28.82
100 % *Parthenium* compost (PC)	0.29	0.07	0.34	0.07	21.44
75 % U + 25 % PC	0.48	0.13	0.53	0.14	30.91
50 % U + 50 % PC	0.54	0.14	0.56	0.17	32.00
25 % U + 75 % PC	0.34	0.09	0.39	0.08	23.52
75 % U + 25 % PC + N fixing bac.	0.58	0.14	0.58	0.18	32.89
50 % U + 50 % PC + N fixing bac.	0.67	0.16	0.68	0.22	34.87
25 % U + 75 % PC +N fixing bac.	0.60	0.15	0.61	0.19	32.66

Parthenium hysterophorus compost improves the physical properties of soil by increasing organic matter content and suppressing soil-borne diseases. Soil porosity and organic matter play a critical role in the biological productivity and hydrology of agricultural soils. The presence of pores influences water infiltration and holding capacity. Increased soil organic matter enhances water retention, improves soil structure, facilitates nutrient exchange, helps soil resist drastic pH fluctuations, and increases nutrient availability (Sonwane et al., 2016).

Incorporating biochar as a soil amendment increases soil porosity, improves soil structure by reducing compaction, and enhances aeration, water, and nutrient-holding capacity. Biochar also raises soil pH, improves soil fertility, and boosts crop productivity, particularly in acidic soils (Muche et al., 2022). The addition of up to 20g/kg of biochar to soil has been shown to increase soil microbial biomass and the activity of several important soil enzymes. *Parthenium hysterophorus* can be converted into biochar by burning it at temperatures between 200°C and 500°C for varying periods in the absence of oxygen (Kumar et al., 2013).

A study on composting *Parthenium* with *Eichhornia crassipes* demonstrated a reduction in the harmful effects of *Parthenium*, while also enhancing the available nutrient content of the compost (Khaket et al., 2015).

Vermicomposting

Conventional vermicomposting technology has been commercially successful primarily when animal manure serves as the substrate. However, vermicomposting of *Parthenium* phytomass has emerged as a promising large-scale utilization of this allelopathic weed (Nayeem et al., 2014; Abbasi et al., 2015). The blending of pre-composted *Parthenium* phytomass with animal manure in comparable or higher quantities has been found to be inefficient and economically unfeasible due to the high cost of animal manure. Alternatively, continuously operable vermireactor systems provide a viable solution for large-scale vermicomposting of *Parthenium* phytomass without the need for pre-composting or manure supplementation (Tauseef et al., 2013).

Soil amended with *Parthenium* vermicompost enhances seed germination and promotes the early growth of seedlings in many crops (*Vigna radiata*-green gram, *Abelmoschus esculentus* ladies finger, *Cucumis sativus* – cucumber). This growth enhancement is reflected in various morphological (shoot/root length, shoot/root fresh weight, and dry weight) and biochemical characteristics (growth hormones, chlorophyll, carotenoids, and tissue nitrogen levels) in plants fertilized with *Parthenium* vermicompost (Silva and Uchida, 2000; Jones, 2012). Studies have shown that *Parthenium* vermicompost stimulates seed germination and promotes early plant growth at concentrations ranging from 0.75–2%, while inhibiting growth at higher concentrations.The compost also contains abundant enzymes, vitamins, antibiotics, plant growth regulators, and a diverse array of beneficial microorganisms.

Parthenium has been shown to support the growth of earthworms, particularly *Eudrilus eugeniae*, when composted, indicating the potential of this weed as an effective substrate for vermicomposting (Biradar et al., 2001). Vermicompost produced from *Parthenium* contains moderate levels of beneficial bacteria, actinomycetes, fungi, phosphate solubilizers, and large populations of *Azotobacter*, with an absence of pathogens. The vermicompost also exhibits low pH, a balanced C:N ratio, and high levels of essential nutrients, all of which contribute to increased crop productivity (Vijaya et al., 2011).

The composition of nutrients in *Parthenium* vermicompost varies depending on the stage of plant growth; vermicompost derived from vegetative plants is richer in nitrogen, while that from flowering plants contains higher phosphorus content (Sarangthem et al., 2009). Notably, vermicompost has low toxicity, as the allelochemicals present in *Parthenium* are degraded during the vermicomposting process (Rajiv et al., 2013).

Generally, vermicomposts derived from various substrates contain more mineral nitrogen in the nitrate form than in the ammoniacal form (Yang et al., 2014). *Parthenium* vermicompost has been found to harbor a rich and diverse microbial population, similar to vermicomposts derived from animal manure. It also introduces beneficial physical features to the growing media and increases the microbial biomass carbon in the soil (Edwards, 2004; Lim et al., 2015). Importantly, the allelopathic biomolecules in *Parthenium* are entirely absent from the vermicompost due to their degradation during the process.

A value added organic fertilizer can be obtained by the management of *Parthenium hysterophorus* through polyculture of the earthworm. It has also been significantly enhancing selected macronutrients, overcome the allelopathic capacity and decrease the organic ‘C’ in compost which is suitable for organic farming (Devi et al., 2021).

Green manure

The addition of green biomass as green manure has been shown to reduce the need for chemical fertilizers, enhance crop growth, and improve the chemical properties of the soil. A similar herbicidal effect and reduction in pest incidence have been observed with *Parthenium* green manure in rice cultivation. Use of green manure one month prior to sowing resulted in better crop growth and higher yields than the recommended dose of NPK fertilizer (Javaid et al., 2010). It is recommended to apply *Parthenium* for manuring at the pre-flowering stage to prevent seed spread. Studies have shown that *Parthenium* green manure increased plant height, the number of filled grains, and straw production, with no weed emergence observed in submerged conditions during rice cultivation (Javaid et al., 2009; Saravanan et al., 2012). Furthermore, *Parthenium* manure enhanced growth and improved nitrogen and phosphorus assimilation in maize crops (Suryawanshi, 2011).

However, the effects of *Parthenium* green manure may vary between plant species. For example, while it has been beneficial for cereal grains, it has shown less positive effects on leguminous crops such as mung bean. This difference may be attributed to plant species specificity in response to allelochemicals (Noor et al., 1994).

From a study by Javaid et al. in wheat cultivation, the application of *Parthenium* green manure resulted in a gradual increase in grain yield with higher manure doses (1 to 4% on a fresh weight basis). Grain yield increased by 43-253% over the control, with a 96% increase due to NPK fertilizers over the control (Figure 1). These benefits were only observed when the pots were left for 30 days after mixing the green plant material with soil, prior to planting, allowing phytotoxic compounds to degrade to some extent during this period.

However, when pots amended with various percentages of *Parthenium* green manure were irrigated with a dilute solution of 0.2% Effective Microbial (EM) cultures at fortnightly intervals, various growth parameters were adversely affected. This may have been due to competition between the added microbes and indigenous soil microbes, or the cultural conditions associated with conventional farming. Consequently, the application of Effective Microbial cultures is not recommended during the first year of application (Javaid et al., 2010).

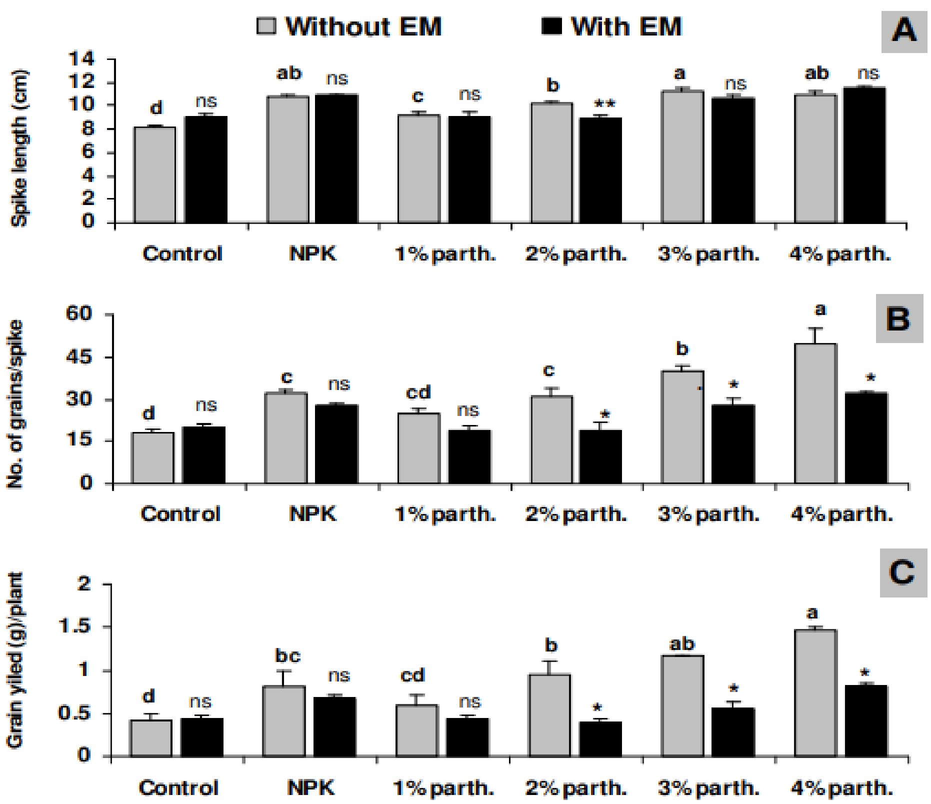

Figure 1: Effect of different percentage of *Parthenium* green manure and Effective Microbe application on some growth parameters of wheat plant . A – Spike length (cm), B – No. of grains/spike, C – Grain yield (g/plant)

A study investigating the influence of *Parthenium* as green manure and its compost on paddy yield parameters found that the application of *Parthenium* compost significantly increased plant height, the number of tillers, grain yield, and straw yield compared to the same level of *Parthenium hysterophorus* used as green manure (Krishnamurthy, 2013).

In an experiment examining the germination and survival rates of radish seeds in normal field soil and in soil amended with *Parthenium* compost, it was observed that the seeds in normal soil took a longer time to germinate, and the emerged plants eventually died due to nutrient deficiencies. No survival was recorded within a month. In contrast, in the *Parthenium* compost-amended soil, 100% germination was observed within the first 15 days, and the survival rate remained 100% within a month. *Parthenium* compost was found to enhance soil fertility and improve soil texture (Ameta et al., 2015) – Figure 2.

Figure 2: Seed germination and growth of Radishes after 30days of compost amendment

Natural herbicides are effective non-chemical methods for weed control in ecologically sustainable agriculture. Plant diseases, including those caused by nematodes and insect pest infestations, can be successfully managed through organic amendments, allelopathic compounds, and crop varieties rich in allelochemicals. Given the practical significance of allelopathy in sustainable agriculture, further research is needed to harness the inhibitory allelopathic effects of plants for the natural control of crop pests and diseases (Narwal, 2010).

Despite the potential benefits of using the allelopathic *Parthenium* weed as a biomanure and biopesticide in sustainable agriculture, its inhibitory effects on seed germination and seedling growth of many crops have been well-documented. The reduction in pasture yield and agricultural productivity can be attributed to several factors, including allelopathic inhibition, contamination of grains and seeds, reduced nodulation in leguminous plants, and the provision of an alternate host for plant viruses and insect pests (Gnanavel et al., 2013). Toxicity due to allelochemicals can be mitigated through composting. While fresh *Parthenium* has been shown to reduce seed germination, *Parthenium* compost only moderately inhibits germination due to the degradation of allelochemicals by microorganisms (Rajiv et al., 2013).

Controlling *Parthenium* in agroecosystems remains a significant challenge. Composting is one of the fastest and most effective methods to recycle this weed into nutrient-rich biofertilizer. Utilizing its abundant biomass for composting also provides an economic and practical approach to managing *Parthenium*. *Parthenium* at the pre-flowering stage is considered the most suitable feedstock for composting due to its soft stems, which decompose more quickly, and its flowers, which are a rich source of allelochemicals (Tejinder et al., 2012).

Conclusion

Parthenium hysterophorus, a highly competitive weed, is nutrient-rich and has the potential to be a valuable resource in ecological agriculture. By utilizing its allelopathic properties, *Parthenium* can be incorporated into composting systems, green manure applications, and bioherbicide formulations. The allelochemicals derived from *Parthenium* have shown promise in weed management and can contribute to the development of novel herbicides, thereby reducing the reliance on synthetic chemical inputs. Composting and vermicomposting of *Parthenium* improve the physicochemical, biological, and nutritional quality of agricultural soils, enhancing soil health and crop productivity. Additionally, the incorporation of *Parthenium* biomass as organic fertilizer helps sequester carbon, reducing CO_2 emissions and mitigating global warming.

The nitrification-inhibiting allelochemicals produced by *Parthenium* play a crucial role in soil nitrification management, improving nitrogen utilization and reducing the emission of nitrous oxide (N_2O). This underscores the potential of *Parthenium* in sustainable agriculture, particularly in organic farming systems. The biodegradation of allelopathic compounds during composting and vermicomposting further enhances its suitability as a soil amendment.

Despite the growing body of research highlighting the agricultural potential of *Parthenium*, its applications remain largely confined to small-scale and regional practices. To fully capitalize on the benefits of this allelopathic weed, further research is necessary to develop innovative composting techniques and biopesticide formulations, as well as to raise awareness about its value in ecological agriculture. By expanding the use of *Parthenium* in larger-scale applications, this underutilized biomass could make significant contributions to sustainable agricultural practices, promoting environmental protection and reducing the reliance on chemical inputs.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Author Contributions

Yapa P. N. proposed the topic on the invaluable wasteland allelopathic weed Parthenium hysterophorus in ecological agriculture and provided guidance on the essential components of the review article. Kapilan R. retrieved full-text research articles and contributed to the development of the manuscript structure and content. Niranjan K. prepared the original manuscript draft in collaboration with all authors.

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