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Research Article

Herbicidal Efficacy of Spiny Pigweed (*Amaranthus spinosus* L.) Leaf Extract for Weed Management in Eggplant (*Solanum melongena* L.)

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ABSTRACT

Weed management in vegetable production increasingly requires environmentally friendly alternatives to synthetic herbicides. This study evaluated the potential of aqueous leaf extract of *Amaranthus spinosus* L. as a botanical weed-suppression agent and its effects on eggplant growth and yield. Four treatments were tested: control (no herbicide) and extract concentrations of 200, 400, and 600 g L^{-1}. Weed cover, weed dry weight, crop growth parameters, yield attributes, and species-specific weed responses were assessed. Results showed that *A. spinosus* extract reduced weed cover (77.13–85.83%) and weed dry weight (183.28–216.63 g $plot^{-1}$) compared with the control (87.37% and 284.93 g $plot^{-1}$), although differences were not statistically significant. The highest concentration (600 g L^{-1}) consistently produced the lowest weed biomass. Eggplant growth and yield parameters, including plant height, number of leaves, number of fruits, and fruit weight, were not significantly affected by the treatments, indicating no phytotoxic effects on the crop. Fruit weight increased from 447.35 g $plant^{-1}$ in the control to 669.05 g $plant^{-1}$ at the highest extract concentration, likely due to reduced weed competition. However, responses varied among weed species, with some showing reduced cover while others exhibited non-linear or increased responses, highlighting species-specific sensitivity to the extract. In conclusion, *A. spinosus* leaf extract demonstrated moderate, non-significant weed suppression without harming eggplant growth, suggesting potential as a component of integrated weed management. However, its efficacy remains limited and requires further validation through detailed dose–response studies, chemical characterization, and field-scale evaluations before practical application.

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Introduction

Eggplant (*Solanum melongena* L.) is an important vegetable crop widely consumed worldwide in both fresh and processed forms. Owing to its high demand and economic value, eggplant is cultivated extensively across diverse agroecological zones, including lowland and highland production systems (Ramadhan et al., 2024). Its cultivation can provide substantial economic returns to farmers; for example, large-scale eggplant production in Africa has been reported to generate profits equivalent to several times the initial investment (Mvungi et al., 2025). In Indonesia, eggplant is also widely cultivated at the household level, particularly by women farmers, contributing to household food security and income generation (Yanez and Paguntalan, 2023; Erwita, 2025).

Eggplant is also recognized for its nutritional and potential health-promoting properties. It is relatively low in calories and provides vitamins, including A, B6, C, and K, as well as essential minerals such as potassium, magnesium, phosphorus, iron, manganese, copper, zinc, and nickel (Abrham and Shumbulo, 2024). In addition, eggplant contains diverse bioactive compounds, including flavonoids, terpenoids, alkaloids, tannins, and other phenolic constituents (Dewi et al., 2025). Its nutritional profile includes proteins, carbohydrates, niacin, thiamine, pantothenic acid, and folate, while its phytochemicals exhibit antioxidant, antimicrobial, and other biological activities (Putri and Fitriana, 2023). These nutritional and phytochemical attributes contribute to the dietary and functional importance of eggplant and may support cardiovascular health and metabolic well-being.

Global eggplant production reached approximately 59.31 million metric tons in 2022, with China, India, Egypt, Türkiye, and Indonesia among the major producing countries (Al-Salmi and Nadaf, 2025). Despite its economic and nutritional importance, eggplant production is constrained by several biotic and abiotic factors, including declining soil fertility, inappropriate agronomic practices, insect pests, plant pathogens, and weeds (Maghfoer et al., 2022; Peralta et al., 2025). Among these constraints, weeds are particularly important because they compete with crops for essential resources, including light, water, nutrients, and space. Some weed species may also serve as alternative hosts for pests and pathogens, thereby facilitating their persistence and spread within agroecosystems (Sahrawat et al., 2020). High weed density can substantially interfere with root and shoot development and consequently reduce crop growth, productivity, and yield (Khamare et al., 2023; Karlsson et al., 2025).

The substantial yield losses associated with weed interference necessitate effective and economically feasible weed-management strategies. Chemical herbicides remain the predominant approach because of their rapid action, broad-spectrum efficacy, and ease of application. However, intensive and inappropriate herbicide use can result in environmental contamination, disruption of soil biological processes, herbicide residues in agricultural commodities, adverse effects on non-target organisms, and the evolution of herbicide-resistant weed populations (Pathak et al., 2022; Kaab et al., 2024). Occupational exposure to pesticides may also pose risks to human health, particularly among agricultural workers who handle and apply these chemicals frequently, with reported associations with respiratory, dermatological, and other chronic health effects (Damalas and Koutroubas, 2016; Ogawa et al., 2023). These concerns have stimulated increasing interest in safer and more sustainable alternatives to conventional chemical weed control.

Botanical herbicides derived from plants represent a promising component of integrated and environmentally sustainable weed-management systems. Plant leaves and other biomass residues that are often discarded or underutilized can serve as inexpensive and readily available sources of bioactive compounds. Plant extracts may offer several advantages, including biodegradability and the presence of diverse phytochemicals with herbicidal or phytotoxic activity (Chahal et al., 2021; Budi et al., 2023). Various plant-derived extracts have demonstrated inhibitory effects against weed germination and growth, highlighting their potential as alternatives or supplements to synthetic herbicides (Hua-long et al., 2023; Wu et al., 2023). In particular, plants can produce a wide range of secondary metabolites that function in defense against herbivores, pathogens, and competing plants. These compounds may exert allelopathic effects by interfering with physiological and biochemical processes in neighboring plants, thereby providing a basis for their exploitation as botanical pesticides and herbicides (Nabavi et al., 2020; Budi et al., 2025).

The herbicidal potential of plant extracts is largely associated with their diverse secondary metabolites, including alkaloids, terpenoids, phenolics, saponins, flavonoids, tannins, and coumarin-related compounds. These compounds can interfere with key physiological processes, including cell division, membrane integrity, nutrient uptake, and photosynthesis, ultimately suppressing weed establishment and growth (Batish et al., 2008). Spiny pigweed (*Amaranthus spinosus* L.), a widely distributed weed species, contains numerous bioactive constituents. Its aqueous extracts have been reported to contain alkaloids, glycosides, steroids, flavonoids, tannins, phenolic compounds, terpenoids, carbohydrates, gums, and saponins (Balakrishnan et al., 2011). The diversity of these phytochemicals suggests that spiny pigweed may possess considerable allelopathic and herbicidal potential.

Therefore, the present study aimed to evaluate the herbicidal efficacy of spiny pigweed extract against weeds associated with eggplant production. The study provides a basis for assessing the potential of this locally available plant resource as an environmentally compatible component of sustainable weed-management strategies in eggplant cultivation.

Materials and Methods

Experimental site and plant material

The experiment was conducted in Karangsari Village, Kembaran district, Banyumas Regency, Central Java, Indonesia, at an elevation of approximately 90 m above sea level. The study evaluated the herbicidal potential of an aqueous leaf extract of spiny pigweed (*Amaranthus spinosus* L.) against weeds occurring in purple eggplant (*Solanum melongena* L.). Yufita F1 was used as the eggplant cultivar. The experiment was conducted under field conditions throughout the crop-growing period.

Experimental design and treatments

The experiment was arranged in a one-factor Randomized Complete Block Design (RCBD) consisting of four treatments with six replications, giving a total of 24 experimental plots. The treatments were:

B0 **=** untreated control (no botanical herbicide);

B1 **=** *A. spinosus* leaf extract at 200 g L^{-1} fresh-leaf equivalent;

B2 **=** *A. spinosus* leaf extract at 400 g L^{-1} fresh-leaf equivalent; and

B3 **=** *A. spinosus* leaf extract at 600 g L^{-1}fresh-leaf equivalent.

Each experimental plot measured 100 × 100 cm, with raised beds approximately 20 cm high. Four Yufita F1 eggplant plants were established in each plot at a spacing of 70 × 70 cm. Adjacent plots were separated by approximately 80 cm to minimize potential interference among treatments. The plot was considered the experimental unit, and the six plots assigned to each treatment constituted the independent replications.

Preparation of *A. spinosus* leaf extract

Healthy and mature leaves of *A. spinosus* were collected and visually inspected to remove damaged, diseased, or contaminated material. The leaves were thoroughly washed with clean water to remove adhering soil and other contaminants and were then air-dried under ambient conditions. Fresh leaf material was weighed according to the required treatment concentration.

For preparation of the 200, 400, and 600 g L^{-1} extracts, 200, 400, and 600 g of fresh *A. spinosus* leaves, respectively, were separately mixed with 1000 mL of distilled water. The leaves were cut into small pieces and homogenized using a laboratory blender until a relatively uniform suspension was obtained. Each suspension was allowed to stand for 24 h at ambient temperature to facilitate the extraction of water-soluble compounds. The resulting suspensions were subsequently filtered through clean gauze to remove coarse plant residues. The filtrates were used directly as aqueous botanical herbicide preparations.

Extract concentration was expressed as grams of fresh leaf material per liter of extraction water (g L^{-1}). Thus, the stated concentrations represent the amount of fresh plant material used to prepare the aqueous extract rather than the concentration of individual active compounds.

Eggplant establishment and application of leaf extract

Yufita F1 eggplant seedlings were transplanted into the prepared plots, with four plants established per plot. The botanical herbicide treatments were initiated 7 days after planting (DAP) and continued at 7-day intervals until 14 days before harvest (Rawnsley, 2020).

Assessment of weed cover and weed dry weight

Weed cover was assessed for each experimental plot following application of the botanical treatments. Weed cover was expressed as the percentage of the plot area occupied by weeds. The same assessment procedure was applied consistently to all experimental plots.

Weeds present in the experimental plots were also identified to species level whenever possible. The percentage cover of individual weed species was recorded under each treatment to evaluate species-specific responses to *A. spinosus* leaf extract.

At the designated assessment, weeds were collected from each experimental plot and their biomass was determined. The collected weed material was dried to a constant weight and weighed using a precision balance. Weed dry weight was expressed as grams per plot (g $plot^{-1}$).

Assessment of eggplant growth and yield attributes

Eggplant growth and yield attributes were evaluated using the four plants established in each experimental plot. The following parameters were recorded:

Plant height (cm): measured from the soil surface to the apical growing point.

Number of leaves ($plant^{-1}$): determined by counting the leaves on each plant.

Number of fruits ($plant^{-1}$): determined by counting the fruits harvested from each plant.

Fruit weight (g $plant^{-1}$): determined from the harvested fruits and expressed as grams per plant.

Measurements obtained from the four plants within each plot were averaged to obtain a single plot-level observation for statistical analysis. Thus, individual plants were treated as subsamples rather than independent experimental replicates.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) appropriate for a one-factor RCBD. The statistical significance of treatment effects was evaluated at the 5% probability level. When significant treatment effects were detected, treatment means were separated using Duncan's multiple range test (DMRT) at $P \leq 0.05$. The assumptions underlying ANOVA, including normality and homogeneity of variance, were assessed before analysis.

Results and Discussion

Weed cover and weed dry weight

The effects of *Amaranthus spinosus* L. leaf extract on weed cover and weed dry weight are presented in Table 1. Weed cover ranged from 77.13% to 87.37%, whereas weed dry weight ranged from 183.28 to 284.93 g plot^{-1}. The untreated control (B0) recorded the highest mean weed cover (87.37%) and weed dry weight (284.93 g plot^{-1}). Although the differences among treatments were not statistically significant, all extract treatments showed numerically lower weed cover and dry weight than the untreated control. The B3 treatment (600 g L^{-1}) produced the lowest values for both weed cover (77.13%) and dry weight (183.28 g plot^{-1}), representing numerical reductions of approximately 11.7% and 35.7%, respectively, relative to B0.

Table 1. Effect of *A. spinosus* leaf extract on weed cover and weed dry weight per plot.

Treatment	Weed cover (%)	Weed dry weight (g plot^{-1})
B0: No herbicide	87.37a	284.93a
B1: 200 g L^{-1}	83.10a	204.60a
B2: 400 g L^{-1}	85.83a	216.63a
B3: 600 g L^{-1}	77.13a	183.28a

Values followed by the same letter within a column are not significantly different according to Duncan's multiple range test (DMRT) at P ≤ 0.05.

The numerical reduction in weed biomass following application of *A. spinosus* extract suggests that the botanical treatment may have exerted some suppressive effects on the weed community, although the absence of statistical significance indicates that these effects were insufficiently consistent among replicates to establish a definitive treatment effect. Plant-derived extracts can contain mixtures of secondary metabolites capable of interfering with seed germination, root and shoot growth, photosynthesis, respiration, and other physiological processes in susceptible plants (Weston et al., 2013; Brunetti et al., 2018; Noguchid and Kato, 2023; Wu et al., 2023; Islam et al., 2024; Patil et al, 2024). Consequently, the effectiveness of an allelopathic extract may vary considerably according to extract concentration, target species, developmental stage, environmental conditions, and the chemical composition of the source plant (Kostina-Bednarz et al., 2023; Satyanarayana Murthy et al., 2025).

The relatively greater numerical reduction in weed dry weight at B3 is consistent with the general expectation that increasing concentrations of plant extracts can increase phytotoxic activity. However, the response was not strictly concentration-dependent because B1 produced a lower mean weed dry weight than B2. Such variation may reflect differences in weed species composition and their differential sensitivity to allelochemicals rather than a uniform response of the entire weed community. Recent field research has likewise demonstrated that plant extracts may exhibit pronounced species-specific effects, with some weeds being strongly suppressed while others remain relatively tolerant (Jalilian et al., 2025).

The results therefore indicate that *A. spinosus* leaf extract has potential as a botanical weed-suppression agent, but its efficacy under the conditions of the present experiment was limited. Further studies involving standardized extraction procedures, chemical profiling of the active constituents, dose-response experiments, and assessment of individual weed species would be necessary to establish its bioherbicidal potential more conclusively.

Plant height, number of leaves, number of fruits, and fruit weight

The effects of *A. spinosus* leaf extract on eggplant growth and yield attributes are presented in Table 2. The extract treatments did not significantly affect plant height, number of leaves, number of fruits, or fruit weight. Nevertheless, numerical differences were evident among treatments. Plant height increased from 57.3 cm in B0 to 63.4 cm in B3, while the number of leaves increased from 45.5 to 49.0 plant^{-1}. Similarly, the mean number of fruits increased from 3.2 plant^{-1} in the control to 4.2 plant^{-1} under B3. Fruit weight showed the greatest numerical response, increasing from 447.35 g plant^{-1} in B0 to 669.05 g plant^{-1} in B3.

Table 2. Effect of *A. spinosus* leaf extract on eggplant growth and yield attributes.

Treatment	Plant height (cm)	Number of leaves plant^{-1}	Number of fruits plant^{-1}	Fruit weight (g plant^{-1})
B0: No herbicide	57.3a	45.5a	3.2a	447.35a
B1: 200 g L^{-1}	62.6a	48.7a	3.7a	554.65a
B2: 400 g L^{-1}	59.7a	48.0a	3.3a	594.28a
B3: 600 g L^{-1}	63.4a	49.0a	4.2a	669.05a

Values followed by the same letter within a column are not significantly different according to DMRT at $P \leq 0.05$.

The absence of significant treatment effects indicates that application of *A. spinosus* extract did not adversely affect the measured growth and yield attributes of eggplant. This is an important finding because botanical extracts intended for weed management should ideally suppress weeds while causing minimal phytotoxicity to the crop. The numerical improvement observed under B3 may partly be associated with the lower weed cover and dry biomass recorded under this treatment (Savić et al., 2025). Reduced weed biomass can potentially decrease competition for light, water, nutrients, and growing space, thereby improving resource availability to the crop. Weed competition is particularly important during periods of rapid crop establishment and canopy development.

Although B3 produced the greatest numerical values for all four crop traits, these differences were not statistically significant. Therefore, the higher fruit weight observed under B3 should be interpreted as a numerical response rather than a demonstrated treatment effect. Nevertheless, fruit weight increased from 447.35 g plant^{-1} in B0 to 669.05 g plant^{-1} in B3, corresponding to a numerical increase of approximately 49.5%. This response is consistent with the possibility that partial suppression of the weed community reduced crop–weed competition. However, because weed cover and dry weight were also statistically non-significant, this interpretation should remain cautious.

Plant-derived allelochemicals can produce complex and species-specific responses. Their effects may range from growth inhibition at sufficiently high concentrations to little measurable effect or even stimulation at lower concentrations, depending on the target species and physiological conditions (Kostina-Bednarz et al., 2023; Thi et al., 2025). The present findings therefore suggest that *A. spinosus* extract did not cause detectable phytotoxicity to eggplant under the tested application regime, while potentially providing some degree of weed suppression.

The underlying mechanisms should not, however, be attributed to specific compounds without chemical characterization of the extract. *A. spinosus*, like many plants, may contain phenolic compounds, flavonoids, terpenoids, alkaloids, and other secondary metabolites, but the present experiment did not establish which compounds were present in the aqueous extract or whether they were responsible for the observed responses (Boncan et al., 2020; Bhambhani et al., 2021; Mora et al., 2022). Allelopathic activity is generally considered to result from the combined or interactive effects of multiple metabolites rather than necessarily from a single compound (Kostina-Bednarz et al., 2023; Satyanarayana Murthy et al., 2025).

Species-specific weed responses to *A. spinosus* extract

The percentage cover of individual weed species under the four treatments is presented in Table 3. The identified weeds have been shown in Figure 1. The response to *A. spinosus* extract varied substantially among weed species, demonstrating that the botanical treatment did not exert a uniform effect across the weed community.

The response of *Ageratum conyzoides*, *Cleome rutidosperma*, *Alternanthera sessilis*, *Gomphrena celosioides*, *Phyllanthus niruri*, *Eleusine indica*, *Mimosa pudica*, *Spigelia anthelmia*, and *Physalis angulata* varied among extract concentrations. In several cases, weed cover increased at one or more extract concentrations rather than showing a consistent decline. For example, *A. sessilis*, *G. celosioides*, and *P. niruri* recorded their highest cover under B3. Similarly, *E. indica*, *M. pudica*, *S. anthelmia*, and *P. angulata* exhibited relatively greater cover at B2 than under the control or lower extract concentrations.

Such non-linear responses may indicate differential species sensitivity to the extract. However, the observed increases should not be conclusively interpreted as hormesis without a properly designed dose-response experiment and statistical testing of the stimulatory response (Jalal et al., 2021; Siemieniuk et al., 2025). Hormesis is characterized by a reproducible biphasic dose-response relationship in which low exposure stimulates a biological response whereas higher exposure produces inhibition. Recent research has documented hormetic responses to plant extracts, including allelopathic extracts used for weed management (Erofeeva, 2022; Parte et al., 2025; Thi et al., 2025).

Table 3. Percentage cover of individual weed species under different *A. spinosus* extract treatments.

Species	Family	Treatment			
		B0	B1	B2	B3
Ageratum conyzoides L.	Asteraceae	2.0d	8.3a	5.0b	3.0c
Amaranthus spinosus L.	Amaranthaceae	12.8a	8.4b	8.2b	8.3b
Alternanthera sessilis L.	Amaranthaceae	2.2c	5.7b	5.8b	10.1a
Celosia argentea L.	Amaranthaceae	12.5a	6.3d	8.2b	7.5c
Gomphrena celosioides	Amaranthaceae	4.2c	5.0b	3.0d	8.0a
Phyllanthus niruri L.	Euphorbiaceae	7.6b	4.8d	5.1c	12.3a
Cyperus rotundus L.	Cyperaceae	8.9a	8.2b	2.4d	5.0c
Typhonium trilobatum	Araceae	2.5a	0.0b	0.0b	0.0b
Cleome rutidosperma	Capparidaceae	4.0b	5.0a	3.7c	3.6c
Eleusine indica L.	Poaceae	2.0d	2.5c	11.0a	6.5b
Mimosa pudica L.	Leguminosae	1.8c	2.9b	3.3a	2.8b
Richardia brasiliensis	Rubiaceae	22.4a	21.6b	16.4c	15.0d
Spigelia anthelmia L.	Loganiaceae	2.8b	2.2c	4.8a	0.7d
Physalis angulata L.	Solanaceae	1.7b	2.2d	8.9a	4.3c

B0 (no herbicide), B1 (spiny pigweed 200gL^{-1}), B2 (spiny pigweed 400gL^{-1}), and B3 (spiny pigweed 600gL^{-1}).

Figure 1. Identified weeds during the assessment.

An alternative explanation is that the extract selectively suppressed some species, indirectly increasing the relative abundance or percentage cover of more tolerant species. Thus, an increase in the percentage cover of a particular weed does not necessarily demonstrate stimulation by the extract; it may also reflect changes in interspecific competition within the weed community. This distinction is particularly important when interpreting community-level responses to botanical herbicides.

In contrast, *C. argentea*, *C. rotundus*, *R. brasiliensis*, and *A. spinosus* generally showed lower cover following extract application. *R. brasiliensis* exhibited a particularly clear numerical decline, from 22.4% in B0 to 15.0% in B3. *A. spinosus* also declined from 12.8% in the untreated control to approximately 8.2–8.4% under the extract treatments. The response of *A. spinosus* is particularly interesting because the extract was prepared from the same species, suggesting the possibility of species-specific tolerance or sensitivity. However, this pattern alone is insufficient to establish autotoxicity, which requires specifically controlled experiments demonstrating inhibition of the same species by its own chemical exudates or extracts. Therefore, the observed response should be regarded as preliminary evidence requiring further investigation.

The strongest species-specific response was observed for *T. trilobatum*, which was recorded in the control treatment (2.5%) but was not detected in any of the extract treatments. This pattern suggests that *A. spinosus* extract may have suppressed this species under the experimental conditions. However, because the initial abundance of *T. trilobatum* and its spatial distribution were not reported, the result should be interpreted cautiously. Additional replicated dose-response experiments are required to determine whether this apparent selectivity is reproducible.

Overall, the species-specific patterns observed in Table 3 support the view that botanical extracts can have differential effects on weed communities. Recent reviews emphasize that allelopathic interactions are influenced by the chemical composition of the donor plant, target-plant susceptibility, extract concentration, environmental conditions, and interactions among multiple allelochemicals (Kostina-Bednarz et al., 2023). Consequently, the efficacy of *A. spinosus* extract should be evaluated not only by total weed cover or biomass but also by changes in individual weed species.

The present findings provide preliminary evidence that aqueous *A. spinosus* leaf extract may contribute to selective weed suppression while maintaining eggplant growth and yield. Nevertheless, the lack of statistically significant effects on overall weed cover, weed dry weight, and crop traits indicates that the extract cannot yet be considered a sufficiently effective standalone bioherbicide. Future investigations should incorporate chemical characterization of the extract, standardized active-compound concentrations, replicated dose-response experiments, longer-term assessment of weed emergence, and comparisons with a registered synthetic herbicide or other appropriate positive control. Such studies would help determine whether *A. spinosus* can be practically integrated into sustainable and reduced-input weed-management programs.

Conclusion

The present study demonstrated that aqueous leaf extract of *Amaranthus spinosus* exhibited a general trend toward reducing weed cover and weed dry weight, although these effects were not statistically significant. Similarly, the extract did not significantly influence eggplant growth and yield parameters, indicating that it was not phytotoxic to the crop under the tested conditions. However, numerical improvements in crop performance, particularly at the highest extract concentration, suggest a possible indirect benefit through partial weed suppression.

Species-specific responses of weeds to the extract were evident, with some species showing reduced cover while others exhibited variable or increased responses, highlighting the complex and selective nature of plant–plant interactions mediated by allelochemicals. Overall, the findings suggest that *A. spinosus* leaf extract has potential as a component of integrated weed management strategies, but its efficacy as a standalone bioherbicide remains limited. Further research involving chemical characterization, optimized extraction methods, and controlled dose–response studies is required to fully evaluate its practical applicability in sustainable agriculture.

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Author Contributions

GPB conceptualized and designed the study. GPB and ODH conducted the fieldwork and experiments. GPB supervised the research and ensured methodological and analytical consistency, while ODH contributed to experimental design, data interpretation, and research refinement. GPB drafted the manuscript, and both the authors critically reviewed, revised, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 15: Life on Land

Policy Addressed

The findings support policies promoting integrated weed management and reduced reliance on synthetic herbicides through botanical alternatives. Further investment is needed in bioherbicide research, phytochemical characterization, formulation, dose optimization, and field validation of Amaranthus spinosus extracts. Regulatory frameworks should ensure efficacy, crop safety, environmental sustainability, and farmer adoption.

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