



ALLELOPATHIC POTENTIAL OF SELECTED INVASIVE ALIEN PLANT SPECIES (IAPS) OF NEPAL AS BIO-HERBICIDE: A SYSTEMATIC REVIEW AND META-ANALYSIS

Til Kumari Chhetri¹, Raj Kumar Thapa^{2*}, Hari Datta Bhattarai^{1*}

¹Central Department of Botany, Tribhuvan University, Kirtipur, Nepal

²Gandaki University, Pokhara, Gandaki Province, Nepal

*Correspondence: haridatta.bhattarai@cdb.tu.edu.np, rkthapa@gandakiuniversity.edu.np

(Submitted: August 7, 2025, Reviewed: December 01, 2025, Accepted: April 27, 2026)

ABSTRACT

Invasive alien plant species (IAPS) have raised the ecological and agricultural concern by rapidly spreading from roadside to the agricultural land, forest and rangeland in Nepal. They suppress the native biodiversity and reduce agricultural productivity by producing allelo-chemicals that contribute to their rapid growth and widespread distribution by inhibiting their growth. Despite their negative impact, the practical implication of allelo-chemicals from invasive alien plant species of Nepal as natural herbicide remains underexplored. Weed infestation in croplands incurs significant economic costs, often requiring the use of chemical or bio-based herbicides for management. However, synthetic herbicides are known to cause various environmental and health concerns. Utilization of allelo-chemicals as bio-herbicide from IAPS could be the sustainable, eco-friendly, and cost-effective approach for effective weed management. The objective of the study was to evaluate the allelopathic effects of IAPS of Nepal for their potential use as bio-herbicides against agricultural weeds. PRISMA flow chart and guidelines were used and search engine included Google scholar, PubMed, AGORA, EBSCO and ProQuest. Studies published between 2014 and 2024 that investigated the use of any one of the five IAPS- *Lantana camara*, *Chromola odorata*, *Pontederia crassipes*, *Mikania micrantha*, or *Sphagneticola trilobata* which are among world's hundred worst IAPS, for weed management, were selected for review. Data regarding growth parameter were extracted from 14 reports comprising 35 studies. The data were analyzed using RevMan software, employing SMD and odds ratio for germination and mean difference and % inhibition for root and shoot length. Weed germination, shoot length, and root length showed significant differences across all comparisons with moderate to strong inhibition observed following treatment with extracts from IAPS. IAPS could have the potential to serve as eco-friendly alternatives to synthetic herbicides for effective weed management but field-based validation is required.

Keywords: Allelo-chemicals, Bio-pesticides, Invasive plants, Weed germination

INTRODUCTION

Allelopathy is the chemical interaction between the plants where the chemicals released by one plant either enhance or inhibit the growth and development of other plant (Rice, 1979). The ecological success of invasive alien plant species (IAPS) is often related to their higher level of allelo-pathic effect on native species that leads to the biodiversity degradation (Hierro & Callaway, 2003; Qu et al., 2021)

Synthetic herbicides cause environmental pollution, human toxicity and development of resistant weed population (Parven et al., 2025). Also, they can contaminate soil, air and water resulting in the long-term risk to human health and the ecosystem conservation (Weidenhamer & Callaway, 2010).

Exposure to the chemical herbicide increases the risk of various health problems linked to cancer, neurological damage and reproductive issues (Kaur et al., 2014), though they are highly effective against weeds.

The adverse effects of synthetic herbicides in agriculture - such as their persistence in food chain, the emergence of herbicide-resistant weeds, and negative impact on human health - have led to an increasing demand of eco-friendly alternatives for weed control (Oaya et al., 2019). Thus, the development of plant-based herbicide is emerging as a promising alternative. IAPs are often regarded as problematic weeds themselves, as they inhibit crop growth, reduce yield and quality, and increase

production costs (Kaur et al., 2014). However, despite their negative impacts, IAPs contain allelochemicals that, when properly applied, have the potential to suppress the growth of other weeds (Erida et al., 2019).

Several allelochemicals -such as glucosinolates from *Brassica* sp., isothiocyanates from *Raphanus sativus* L., sorgoleone from *Sorghum bicolor* (L.) Moench, momilactone from moss and rice, artemisinin from *Artemisia annua* L., leptospermone from *Calistemon citrinus* (Curtis) Skeels, essential oils from *Eucalyptus* sp., and sermentine from *Pepper* sp. have been used as bio-herbicides to control various weeds, including *Amaranthus hybridus* L. and *Cassia occidentalis* L. (Soltys et al., 2013). In Nepal, allelopathy of IAPS like *Lantana camara*, *Ageratum conyzoides* and *Parthenium hysterophorus* and some medicinal plants were studied against agricultural crops (Shrestha & Thapa, 2018; Acharya et al., 2022) but limited study had performed against agricultural weeds. However, the large quantities of allelochemical required for effective weed control limit industrial scalability and commercial use of bio-pesticide.

Recent studies have explored allelopathy of IAPS such as *Ageratina adenophora* (Spreng) R. M. King & H. Rob (Khatri et al., 2025) and *Parthenium hysterophorus* L. (Hassan et al., 2018) for their potential as bio-herbicidal sources but the practical implication for the use of IAPS as bio-herbicides remains underexplored. The use of IAPS in bio-herbicide formulation could offer a cost-effective solution, leveraging their abundance, rapid growth, and high biomass production (Weidlich et al., 2020).

This review aims to explore the allelopathic potential of five high risk IAPs in Nepal: *Lantana camara* L., *Chromolena odorata* (Spreng) R. M. King & H. Rob, *Pontederia crassipes* Mart., *Mikania micrantha* Kunth, or *Sphagneticola trilobata* (L). This systematic review and meta-analysis seek to evaluate the herbicidal potential of those IAPS against the agro-weeds. By identifying eco-friendly alternatives to synthetic herbicides, this work contributes to the development of sustainable weed management strategies in Nepal and other ecosystems facing similar invasive species challenges.

METHODS

Eligibility criteria (PICOST)

This review included all relevant observational studies (of any type) and randomized controlled trials that investigated the use of selected IAPS as bio-herbicides in weed management. Eligible studies

involved treatments using extracts from any of the five IAPs prevalent in Nepal-*Lantana camara*, *Chromolena odorata*, *Pontederia crassipes*, *Mikania micrantha* and *Sphagneticola trilobata* applied to assess their effects on weed germination and growth parameter under controlled, semi-natural, or natural conditions.

Studies were excluded if appropriate control groups were not used. The primary outcome was to determine the allelo-pathic potential of the selected IAPS as bio-herbicides. Secondary outcomes included comparisons of germination percentage, shoot length, and root length of weeds only, between treated and control groups, along with associated standard deviations. Studies focused solely on ecological assessments without direct testing of bio-herbicidal properties were excluded.

Participants

Studies assessing any one of the five IAPs of Nepal-*Lantana camara*, *Chromolena odorata*, *Pontederia crassipes*, *Mikania micrantha*, and *Sphagneticola trilobata* used as bio-herbicides against various weed species were considered eligible for inclusion.

Interventions

Eligible interventions included treatments using extracts from any one of the five selected IAPs aimed at inhibiting weed germination or affecting growth parameters.

Comparators

Comparative data included measurements of germination percentage, shoot length, and root length in treated versus untreated (control) weed samples.

Outcomes

Studies were included if they reported at least one of the following outcomes: germination percentage, shoot length, or root length with or without standard deviation.

Study design

Observational studies (of any type) and randomized controlled trials conducted under natural, semi-natural, or controlled conditions were included.

Time Frame

Only studies published between 2014 and 2024 were considered for this review.

Search strategy

The search strategy included the following keywords and Boolean operators: "Allelopathic effect *Chromolena*" OR "*Pontederia*" OR "*Mikania*" OR

“*Lantana*” OR “*Sphagneticola*” OR “Herbicidal potential”. Searches were conducted across multiple data-base -PubMed, AGORA, Google Scholar, EBSCO, and ProQuest-between October 23 and 25, 2024 (Appendix 1 for full search strings).

Search filters were applied to limit results to relevant publication types. Exclusion criteria included books or book chapters, articles in press, conference abstracts, and thesis. Only peer-reviewed articles published in English were considered.

All search results were de-duplicated using the Systematic Review Accelerator (SRA) tool and further screened manually. Additional studies were identified through reference list checks of included articles. Supplementary searches were conducted by the author (TC). Reference management was performed using Zotero.

Study screening

Title and abstract screening was conducted independently by two reviewers based on predefined eligibility criteria. Following this initial screening, the full texts of potentially relevant study by either reviewer were retrieved and assessed for final inclusion. Any disagreement on full text assessment between both reviewers were resolved through discussion. The entire selection process was documented in detail to enable the completion of a

PRISMA (Preferred Reporting Items for Systematic review and Meta-Analysis) flow diagram.

Data extraction

Data were extracted using a standardized form, which was initially piloted on three included studies to ensure consistency. For each eligible study, relevant information was collected from tables, figures, result descriptions, or relevant headings. The extracted data included:

- Study types: Observational studies (all types) and randomized controlled trials
- Methods: Germination percentage, growth parameters, authors, publication year, study duration, sample size and replicates, standard deviations, plant formulations, experimental methods, and study design
- Participants: All types of weed species targeted in the studies
- Interventions and Comparators: Types of plant extract used, herbicidal potential, and mean differences between treated and control groups.
- Outcomes: Changes in germination percentage, shoot length, and root length

Assessment of risk of bias

The quality assessment was conducted by two reviewers at once using Cochrane risk of bias tool for the included studies (Fig.1).

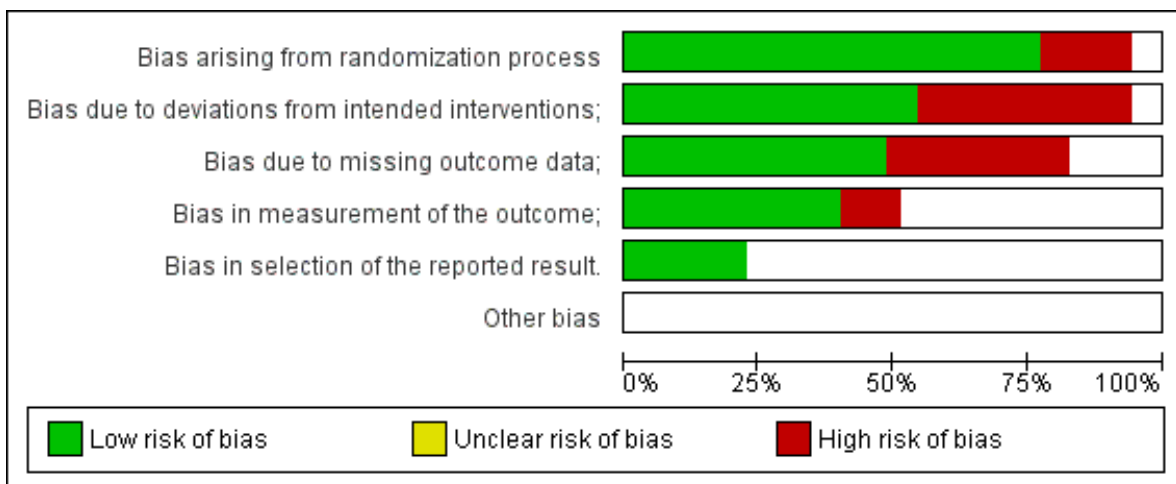


Figure 1. Risk of bias graph

Measurement of effect

Intervention effects were analyzed using RevMan 5.4.1, supported by the SRA tool. For dichotomous outcomes (germination on treated vs control), odds

ratios were calculated. Continuous outcomes were measured using standardized mean differences to those having standard error and standard deviation. A meta-analysis using a random-effects model was

conducted when sufficient studies with comparable outcomes were available. Results were expressed with 95% confidence interval for all outcomes.

Unit of analysis

The primary unit of analysis was whether extracts from invasive plant species reduced weed germination and growth. Forest plot was used to display the result and studies with missing data were discussed using average differences in percentage of growth parameter in control and treated samples. Methodological variability among the studies may increase the heterogeneity and make outcome less reliable.

Missing data strategy

No efforts were made to contact original study authors or sponsors for missing data. For the studies with incomplete data, qualitative synthesis was done and excluded from quantitative analysis. Thirty studies with missing complete data were excluded from quantitative analysis. Events counts were approximated from mean germination percentage of

27 studies assuming same sample size across the replicates were pooled for effect size. The missing data regarding shoot length and root length in thirty studies were analyzed qualitatively by calculating mean difference (MD) and % inhibition of growth.

Assessment of heterogeneity

Heterogeneity was assessed using the I^2 and tau squared statistics to evaluate variability among the included studies. Review manager 5.4.1 was used for assessment.

Assessment of publication biases

Publication bias was evaluated using Funnel plots.

RESULTS

The initial search yielded 436 records. After removing duplicates, 395 unique studies remained. Title and abstract screening excluded 328 studies. Of the remaining 67, full-text screening excluded an additional 53 studies. Ultimately, 14 publications comprising 35 individual studies were included for data extraction (Fig. 2).

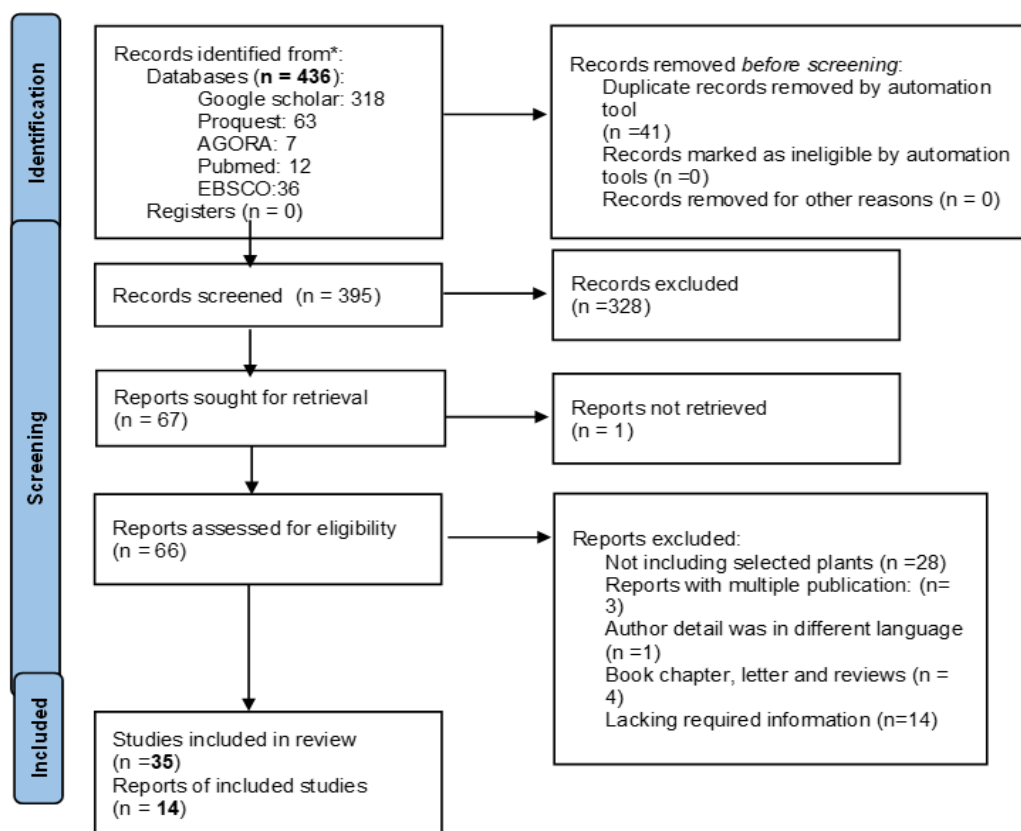


Figure 2. PRISMA flowchart

Distribution of studies by plant species

- *Lantana camara*: 19 studies
- *Pontederia crassipes*: 6 studies
- *Chromolena odorata*: 5 studies
- *Sphagneticola trilobata*: 3 studies
- *Mikania micrantha*: 2 studies

Herbicidal potential of different IAPs

Lantana camara

Among the included studies, *Lantana camara* was evaluated for its herbicidal potential against a range of weed species, including *Euphorbia helioscopia* L., *Chenopodium album* L., *Avena fatua* L., *Rumex dentatus* L., *Phalaris minor* Retz. (Anwar & Qureshi, 2021), *Ludwigia decurrens* Walter, *Ludwigia hyssopifolia* (G. Don) Exell (Ranwala et al., 2015) *Bidens pilosa* L. (Gindri, 2020) and *Galinsoga parviflora* Cav. (Daba, 2021). Treated samples consistently exhibited lower germination percentages compared to controls. Notably, *Ludwigia hyssopifolia* showed only 11% germination when treated with 4 g of *Lantana* leaf powder mixed with 85 g paddy soil in a 65 mm pot over 22 days. Similarly, a 5% aqueous extract of *Lantana* resulted in 27% germination of *Bidens pilosa* after seven days compared to 42% germination in control experiment. Although hexane extracts of the dried leaves were commonly used in included studies, the aqueous extract and powder itself are comparatively more effective showing germination inhibition ranged from 55-90% compared to only 19% to 50% of hexane extract, suggesting moderate to high efficacy of the plant as herbicide.

Pontederia crassipes

Extract and powder from *Pontederia crassipes* was tested against *Cyperus esculentus* L., *Amaranthus tricolor* L., and *Ambrosia artemisiifolia* L. (Fu et al., 2020). Biomass of *Amaranthus tricolor* biomass was reduced by 50% and 44% using 0.1 g and 1 g of powder, respectively ($p=0.011$), with an overall 49% reduction in growth. However, in contrast, germination of *Ambrosia artemisiifolia* was increased by 350% following treatment with 0.5 g powder under green-house conditions, indicating potential species-specific interactions.

Chromolena odorata

Methanol extracts of *Chromolena odorata* significantly reduced root length in *Amaranthus spinosus* L. under semi-natural conditions, with treated samples showing an average of 22.17 cm

versus 33.17 cm in controls; however, shoot lengths did not differ significantly (Erida et al., 2019). In another study, ethanol and crude hexane extracts yielded only 7.5% and 1.25% germination of *Echinocola crusgalli* (L.) Beauv. seeds, respectively, while no germination was observed in *Amaranthus viridis* L. under the same treatments (Poonpaiboonpipat et al., 2021). These findings indicate strong allelopathic potential against various weed species. There was no record of aqueous extract of *Chromolena odorata* on weed germination in the included studies.

Mikania micrantha

In a petri plate bioassay, methanol extracts of *Mikania micrantha* completely inhibited germination of *Echinochloa colona* L., whereas 84% germination was observed in the control group excluding extract. (Lim, 2017). However, a study by Alridiwirah et al. (2022) found no significant difference in root length between treated (39.4 cm) and control (35.3 cm) samples of barnyard grass using ethanol extracts, highlighting variability in efficacy depending on experimental conditions.

Sphagneticola trilobata

Aquades of *Sphagneticola trilobata* significantly inhibited various growth parameters ($P=0.05$) of *Cyperus rotundus* L., including shoot length, root length, fresh weight, and dry weight under greenhouse conditions (Uyun et al., 2024). Moreover, only 5% germination of *Eupatorium catarium* Veldkamp was reported after treatment with aqueous extracts in a controlled experiment (Dai et al., 2016). Leachates also affected *Wedelia chinensis* (Osbeck) Merr., with treated samples exhibiting reduced shoot length (11 cm vs. 13 cm), root length (9 cm vs. 16.5 cm), fresh weight (0.4 g vs. 1.8 g), and comparable dry weight (0.41 g vs. 0.39 g) compared to controls (Ullah, 2021)

Formulations of bio-pesticides

Various formulations of bio-pesticides were evaluated across the reviewed studies, including aqueous extracts, hexane and ethanol extracts, plant powders, leachates, and essential oils. The efficacy of these formulations varied depending on the target weed species. Notably, ethanol and crude hexane extracts of *Chromolena odorata* resulted in less than 10% germination in *Amaranthus* and *Echinochloa* species (Poonpaiboonpipat et al., 2021), while aqueous extracts of *Sphagneticola trilobata* suppressed *Eupatorium catarium* germination to similarly low levels (Dai et al., 2016). Additionally,

aqueous extracts and powdered formulations of *Lantana camara* and *Pontederia crassipes* reduced germination of *Ludwigia decurrens*, *Ludwigia hyssopifolia*, *Bidens Pilosa*, and *Ambrosia artemisiifolia* by over 50% (Ranwala et al., 2015; Fu et al., 2020; Gindri, 2020). Among the tested formulations, aqueous extracts emerged as the most commonly used and studied, followed by hexane and ethanol extracts.

Plants used for bioassay

The herbicidal bioassays included a diverse range of both dicotyledonous and monocotyledonous weed species. The tested plants comprised *Cyperus rotundus*, *Phalaris minor*, *Cyperus esculentus* L., *Amaranthus tricolor*, *Ambrosia artemisiifolia*, *Ludwigia decurrens*, *Ludwigia hyssopifolia*, *Bidens pilosa*, *Amaranthus spinosus*, *Echinochloa crus-galli*, *Echinochloa colona*, *Amaranthus viridis*, *Eupatorium catarium*, *Wedelia chinensis* and *Galinsoga parviflora*. Notably, some studies (Erida et al., 2019; Gindri, 2020) also evaluated the allelopathic effects of plant extracts on *Bidens pilosa* and *Amaranthus spinosus*, which themselves are classified as IAPS in Nepal. This highlights both the complexity and relevance of species selection in bio-herbicidal research.

Duration of treatment and experimental conditions

The reviewed studies employed four experimental designs: controlled petri plate bioassays, control greenhouse experiments, semi-controlled pot experiments, and natural condition trials. Most investigations were conducted under controlled conditions, with only a few utilizing pot experiments and a single study conducted in a natural setting. Treatment duration varied from 7 days to 6 weeks, influenced by the type of formulation used, the weed

species tested, and the specific experimental setup. Notably, experiments conducted in natural and semi-controlled pot conditions generally required longer observation periods compared to petri-plate and greenhouse bioassays

Effect of plant extracts on weed germination (based on standard deviation)

Only five studies reported sufficient data-including means, standard deviations or standard errors, and total seed counts-covering a combined sample size of 1,320. A high degree of heterogeneity was observed ($I^2 = 99.82\%$). A significant difference was found between treated and control groups, with a standardized mean difference (SMD) of -18.11 (95% CI: -32.48 to -3.73; $p < 0.05$) (Fig. 3). The negative SMD indicates a substantial reduction in weed germination following treatment with plant extracts. These findings support the herbicidal potential of extracts from selected invasive alien plants. The funnel plot (Fig. 4a) appeared symmetrical suggesting minimal risk of publication bias. Four of the studies in this analysis are of aqueous extract and powder of *Lantana camara* on different weeds. The funnel plot (Fig. 4b) shows possible publication bias for this outcome which suggest that the included studies overstated the efficacy of those IAPS as potential herbicide and underreporting the neutral or less significant findings.

Massive SMD reflect the high potential of *Lantana camara* as bio-herbicide but because of high heterogeneity, it can't be fit to all weeds. The potency could be on laboratory condition but its variability may be because of type of solvent used for extraction, form of extract, environment and allelo-chemical present on it and treated weed species.

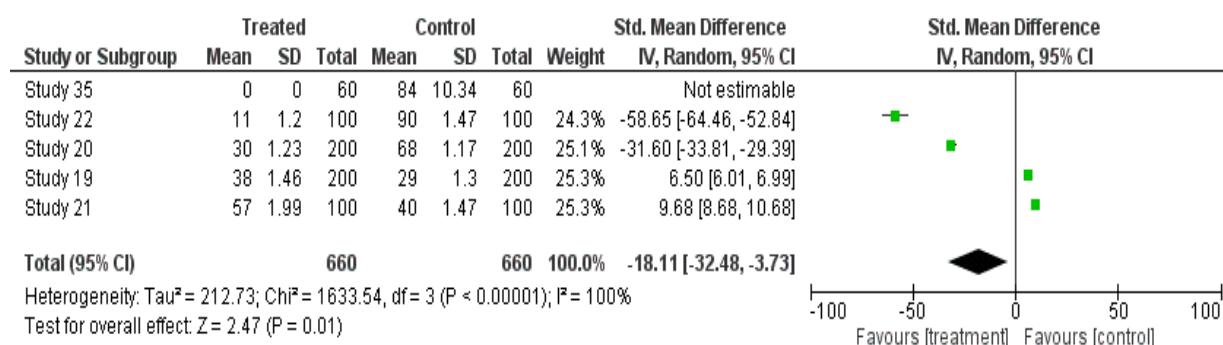


Figure 3. Effect of IAPS extract on germination of weeds

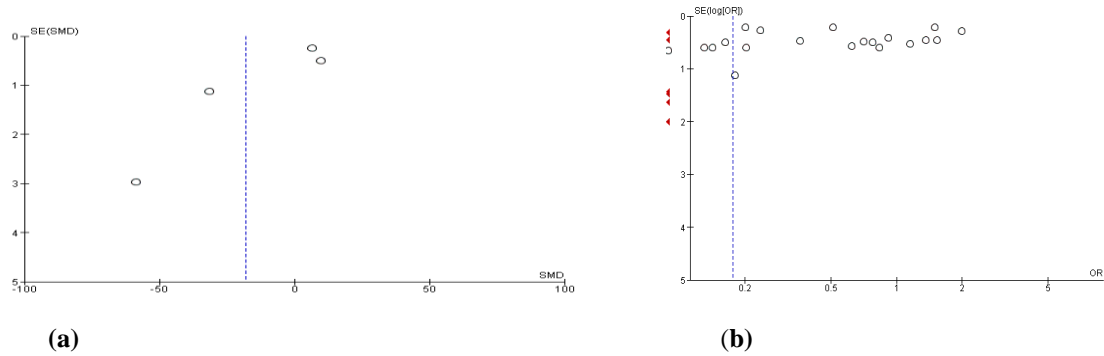


Figure 4. (a) Funnel plot for effect on weeds germination (data with SE and SD); (b) Funnel plot for effect on weeds (data with sample size and mean germination). (SE- standard error; SMD- standard mean difference; SD- standard deviation, X-axis: Effect size and Y-axis: Study precision)

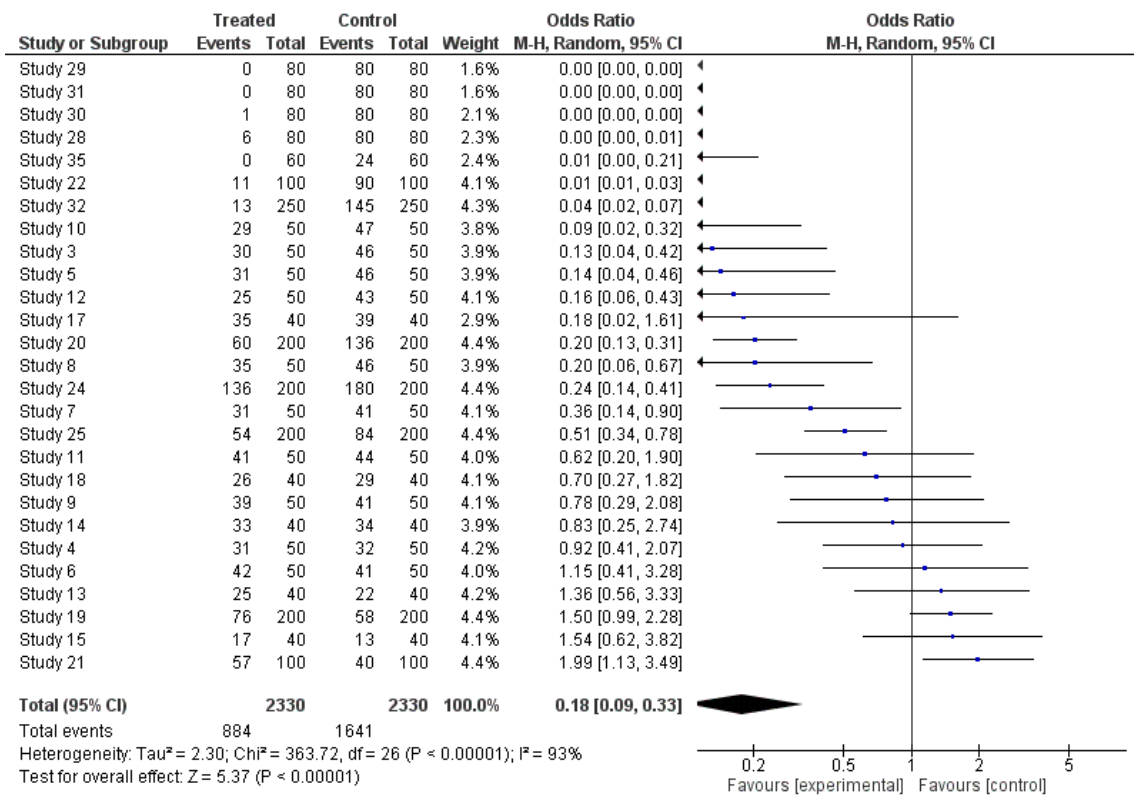


Figure 5. Effect of IAPS extracts on weed germination based on sample size and mean germination %

Effect of IAPS extracts on weed germination (based on sample size and mean germination %)

Twenty-seven studies (total n = 4660) were included in this analysis. High heterogeneity was observed (I² = 93%). A significant difference was found between treated and control groups, with an odds ratio of 0.18 (95% CI: 0.09 to 0.33; p<0.00001), indicating 82% reduction in the odds of weed germination following treatment. Reported reductions in germination ranged from 67% to 91%, confirming the strong herbicidal efficacy of IAPS extracts (Fig. 5). High heterogeneity suggests that there is no uniform effect

size across the studies and this variability may be because of methodological variation of extraction, application, concentration and duration of treatment, differences in the allelo-chemicals in varied IAPS, sensitivity of targeted weeds and the environmental variation. These results are statistically significant (p<0.05), supporting the potential of IAPS as effective sources of bio-herbicide under controlled condition but practical applicability is limited. Thus, rather than all IAPS, only specific IAPS and specific formulation could have herbicidal potential on specific target.

Effect of IAPS extract on shoot length of weeds

A total of 16 studies (n= 1702) does not provide SD or SE, so that the effect of the extract of IAPS on weed germination was compared by calculating % inhibition and mean difference (MD) from averaged values in each study. Among the studies, only one showed strong inhibition (>70%); eight studies showed moderate inhibition (30–60%); and remaining seven studies showed weak inhibition (<30%). Four studies showed no impact of IAPS

extract on shoot length of weeds (MD=0); one study simulated the growth (MD= negative value) and other all studies inhibited the shoot length of weeds (Md=positive value) (Table 1). Thus, *Lantana* (aqueous extract) showed potential as herbicide (Ranwala et al., 2015; Carrubba et al., 2020) but its hexane extract showed no effect on any weeds (Anwar & Qureshi, 2021). The IAPS showed species specific as well as formulation specific effect on shoot length of weeds.

Table 1. Effect of IAPS extract on shoot length

Studies	Mean shoot length (Treated)	Sample size (treated)	Mean shoot length (control)	Sample size (control)	Mean Difference (MD)	% Inhibition
Study 10	5	50	9	50	4	44.44
Study 11	4	50	9	50	5	55.56
Study 12	8	50	8	50	0	0
Study 19	0	200	4	200	4	100
Study 2	21	40	39	40	18	46.15
Study 26	2	3	3	3	1	33.33
Study 3	7	50	8	50	1	12.5
Study 33	13	18	11	18	-2	-18.18
Study 34	7	45	18	45	11	61.11
Study 35	7	45	18	45	11	61.11
Study 4	8	50	9	50	1	11.11
Study 5	5	50	9	50	4	44.44
Study 6	5	50	9	50	4	44.44
Study 7	7	50	7	50	0	0
Study 8	8	50	8	50	0	0
Study 9	9	50	9	50	0	0

Effect of IAPS extract on root length of weeds

Eighteen studies (n = 2,152) reported the effect of IAPS extracts on root length of varied weed species. Two studies (35 and 20) showed strong inhibition on root length of weeds, which comprise methanol extract of *Mikania* and aqueous extract of *Lantana* respectively (Ranwala et al., 2015; Lim, 2017). Eight studies including the effect of *Sphagneticola lobata*

(Ullah, 2021; Uyun et al., 2024) showed moderate inhibition requiring higher concentration for herbicidal effect and other eight studies comprising hexane extract of *lantana* (Anwar & Qureshi, 2021) and ethanol extract of *Mikania* (Alridiwersah et al., 2022) showed weak inhibition or remains neutral for the root length of weeds. Root length of weeds also dependent on type of extract of varied species (Table 2).

Table 2. Effect of IAPS extract on root length of weeds

Studies	Mean root length (treated)	Sample size (treated)	Mean root length (control)	Sample size (control)	Mean Difference (MD)	% Inhibition
Study 26	22	3	33	3	11	33.33
Study 27	35	15	39	15	4	10.26
Study 35	0	45	27	45	27	100
Study 2	21	40	39	40	18	46.15

Study 33	9	18	17	18	8	47.05
Study 20	6	200	23	200	17	73.91
Study 19	1	200	3	200	2	66.67
Study 34	12	45	20	45	8	40
Study 6	5	50	8	50	3	37.5
Study 10	6	50	9	50	3	33.33
Study 5	6	50	9	50	3	33.33
Study 11	5	50	5	50	0	0
Study 12	7	50	7	50	0	0
Study 3	7	50	7	50	0	0
Study 4	8	50	8	50	0	0
Study 7	7	50	7	50	0	0
Study 8	7	50	7	50	0	0
Study 9	8	50	8	50	0	0

DISCUSSION

This meta-analysis reviewed 35 studies examining the allelopathic effects of plant extracts from five IAPS found in Nepal-*Lantana camara*, *Chromolena odorata*, *Pontederia crassipes*, *Mikania micrantha* and *Sphagneticola trilobota* on weed germination and growth parameters under natural, semi-natural, and controlled conditions. Our findings indicate that specific IAPS with specific formulation exhibit moderate to strong inhibitory effects to specific weed species. Notably, the most significant impact was observed on seed germination, while moderate effects were found on shoot and root growth. The pooled effect sizes suggest that crude plant extracts from these IAPS could have potential herbicidal effect and serve as a promising, sustainable alternative to synthetic herbicides for weed management but field-based research for specific IAPS and weed is required for real world efficacy.

Previous reviews and meta-analysis, such as Khamare (2022), support the herbicidal potential of plant-based bioactive compounds, primarily focusing on non-invasive and medicinal plants. A review on biomass from allelopathic agroforestry and invasive alien plant species as soil amendment for weed control (Valiño et al., 2023) had discussed the use of biomass from several IAPS including *Lantana camara*, *Ageratina adenophora*, *Parthenium hysterophorus*, *Cassia* sp., *Amaranthus* sp., *Alternanthera philoxeroides*, *Mikania micrantha*; for integrated weed management suggesting the high cautions for their dispersal. The main sources of bio-herbicide explored till date are fungi and plants but the resource availability is the challenge for industrial scale plant-based herbicide production (Roberts, 2022). However, the application of varied extract formulations from IAPS which are the burden

of ecosystem, as bio-herbicides remains largely unexplored both in national and global context. This study adds a novel contribution by systematically reviewing and analyzing the potential of IAPS in suppressing both pre-emergence and post-emergence growth of a wide range of weed species (Appendix 2), thus highlighting their unexplored allelo-pathic potential for integrated weed management.

The rapid spread and ecological dominance of IAPS in natural environments are often attributed to their allelo-pathic properties, which are linked to the production of high concentrations of allelo-chemicals (Soltys et al., 2013). The observed reductions in germination rates and growth metrics among treated weed species may be due to these bioactive compounds (Khamare, 2022). *Lantana camara* and *Sphagneticola trilobata*, with pronounced herbicidal potential, contains allelochemicals like flavonoids, sequesterpenes, triterpenes and phenolic compounds (Kato-Noguchi & Kurniadi, 2021) which suppresses native species. The variability of effectiveness of the extract among the IAPS and their formulations could be the variation in allelo-chemicals and their quantity; but the duration required to degrade powder of varied species could also have variation in their effect on targeted weeds. This supports the potential of IAPS as an eco-friendly, cost-effective, and sustainable source of herbicidal agents. But the herbicidal efficacy is formulation dependent, concentration dependent, sensitivity dependent for targeted weeds and most importantly species specific.

Despite these promising results, several limitations must be acknowledged. Considerable heterogeneity was found across the included studies, including variations in extract formulations, weed species tested, methodological approaches, treatment

durations, and extract concentration (Table S2). This variability may have influenced the pooled effect sizes. Additionally, in some cases, data were extracted from figures, potentially introducing approximation errors. Environmental variables, often excluded from the studies, may also vary due to geographical differences, which could limit the generalizability of our findings. Because of high heterogeneity among studies, species specific IAPS could have herbicidal potential but their practicability is limited to laboratory testing only and required field-based investigation for real world applicability.

Future research should focus on evaluating the herbicidal potential of region-specific IAPS on local weed species to enhance practical relevance. Further work should also include the extraction, isolation and identification of active compounds, development of standardized formulations, large scale production, and rigorous field testing under agricultural conditions for potential IAPS like *Lantana camara*, *Sphagneticola trilobata*, and *Mikania micrantha* for field-based validation. As this meta-analysis is focused to only five IAPS of Nepal, further investigation is required to support allelopathy of IAPS as bio-pesticide.

Given the growing concerns over the adverse impacts of synthetic herbicides on human health and the environment, and the ecological threats posed by IAPS, policymakers should support and incentivize research into the use of allelo-chemicals from IAPS with potential herbicidal activity; and their effects on non-target organism. This dual-purpose approach could contribute to sustainable weed control while managing the spread of invasive species. Industrial stakeholders may also consider the commercialization of IAPS-based bio-herbicides in regions where these plants are prevalent but their level of toxicity should be investigated and addressed with cautions prior to moving towards formulations.

Overall, this meta-analysis demonstrates the substantial potential of selected IAPS as effective bio-herbicides for managing a wide range of weed species.

CONCLUSION

The findings of this meta-analysis have significant practical implications for sustainable weed management, ecological restoration, and cost-effective herbicide production. The use of IAPS on raw materials for bio-herbicide formulation offers an innovative solution that simultaneously addresses the management of invasive species and reduces

dependency on synthetic chemical herbicides but field validation is required.

This meta-analysis highlights several key areas for future research. Priority should be given to: standardizing methodologies (laboratory based –pot based – field based study) for assessing herbicidal potential; evaluating long-term efficacy and environmental safety by the investigation of allelo-chemicals on soil residue; investigating impacts of herbicide use on crop productivity; optimizing extraction methods and formulation protocols for higher potency; conducting field trials for the effect of IAPS based herbicide across varied agro-ecological zones to investigate the role of environmental variability; exploring regional IAPS with allelo-pathic potential against crops or dominant weed; isolating and characterizing bioactive compounds with herbicidal activity. Continued research in these areas can help to unlock the full potential of IAPS as a sustainable and effective component of integrated weed management strategies.

ACKNOWLEDGMENTS

None

AUTHORS CONTRIBUTION

Conceptualization: TKC, HDB; Methodology: TKC, RKT; Validation: HDB; Investigation: TKC; Data analysis: TKC, RKT; Writing-original draft: TKC; Writing-review & editing: HDB, RKT, TKC; Supervision: HDB, RKT

FUNDING

None

ORCIDs

Til Kumari Chhetri:

<https://orcid.org/0009-0009-3248-9473>

Raj Kumar Thapa:

<https://orcid.org/0009-0004-7488-7465>

Hari Dutta Bhattarai:

<https://orcid.org/0000-0003-2313-1620>

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

ETHICAL STATEMENT

This review has not been previously published elsewhere.

DATA AVAILABILITY STATEMENT

All the data are available as the supplementary materials.

SUPPLEMENTARY INFORMATION

Table S1. Search Strategies

Table S2. Data collected from the study

Table S3. PRISMA 2020 Checklist

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