Evaluation of Allelopathic Potential of Plant Extracts Against Common Weed Species Under Vivo Conditions

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Research Article

Keywords: Allelopathy, Bioherbicides, Plant extracts, Weed management, Sustainable agriculture

Posted Date: February 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8821148/v1

Additional Declarations: No competing interests reported.

Abstract

Weeds severely threaten crop productivity by competing for essential growth resources, while increasing herbicide resistance and environmental risks associated with synthetic chemicals necessitate eco-friendly alternatives. This study evaluated the allelopathic potential of different plant-based extracts, including Walnut (Juglans nigra) bark, Sugarcane (Saccharum officinarum) bagasse, Parthenium (Parthenium hysterophorus) solution, Tumha (Citrullus colocynthis), Algal water extract, Phalaris minor leaves extract, Vinegar, and Tap water (control), against six problematic weed species: Phalaris minor, Melilotus indicus, Cirsium discolor, Cucumis pubescens, Cyperus rotundus, and Convolvulus arvensis. Experiments were conducted under vivo conditions in a completely randomized design with five replications. Results revealed that Walnut bark, Algal water, and Vinegar exhibited the strongest inhibitory effects on seed germination, germination energy, chlorophyll content, shoot and root growth, and overall biomass accumulation. Field thistle and Cucumis were the most sensitive species, showing minimum germination (0.30–0.53), whereas Phalaris minor showed the highest tolerance with maximum germination (79.25%) and biomass accumulation. Sugarcane bagasse and Parthenium demonstrated moderate suppression, while Phalaris minor extract showed limited autotoxic effect on its own species. Overall findings confirm that plant-derived allelopathic extracts, particularly Walnut bark, Algal water, and Vinegar, possess strong bioherbicidal potential and may serve as sustainable weed management alternatives; however, higher concentrations or combined strategies are required for highly resistant weeds such as Phalaris minor and Cyperus rotundus. Moreover, further investigation and integration with reduce herbicides will help in noxious weeds management practices.

Introduction

Weeds are plants with distinct characteristics that deliberately grow out of their place, competing with crops for growth components and resulting in crop economic losses. Weeds are the oldest pollutants in the agriculture environment, and man has long disregarded and accepted this reality. Every weed is physiologically a distinct creature, and each species has its own morphology, ecology, life cycle, reproductive and physiological activity. Their significance has long been emphasized by detailing the magnitude of losses due to weeds which are 25–75% (Farooq et al., 2013). The allelopathic potential of many plants can be used to suppress weeds without having to introduce weed control agents into the field. Non-conventional weed management techniques are becoming increasingly important due to issues with pesticide resistance in weeds, environmental degradation, and the growth of organic agriculture. Proper utilization of the phenomenon of allelopathy could be beneficial in controlling weeds in agricultural settings (Jabran, 2017).

Plants contain natural compounds, some of which are allelopathic, releasing allelochemicals that affect neighboring vegetation. These compounds, ranging from high to low molecular weight, can be released through leaching, volatilization, root exudation, and seed-coat exudation (Rudrappa et al., 2008). Plant organs such as seeds, stems, leaves, flowers, and roots release these compounds, which can have positive or negative environmental impacts (Madanat et al., 2016). Chemical weed control acts quickly, but many weeds are developing resistance to herbicides, which are environmentally harmful. The chemical industry's release of toxic compounds is contributing to environmental degradation, making weed management a critical issue for the crop industry. There is an urgent need for safer, more sustainable weed control methods to protect the ecosystem. Plants and plant materials, rich in primary and secondary metabolites (allelochemicals), are gaining attention as potential agents for weed control. This research will examine plant materials, such as Walnut (Juglans nigra) bark, Tumha (Citrullus colocynthis), Dumbi site (Phalaris minor), Green water algae, Sugar cane (Saccharum officinarum) bagasse, and Vinegar, for their allelopathic and phytotoxic properties. The study aims to evaluate their impact on weed germination and growth, assess the potential of plant phytoextracts to suppress weed growth under controlled conditions, and investigate the resistance of weeds to the phytotoxic effects of these plants.

Materials and Methods

Place of work and facilities available

In this experiment, impact of various plant extracts was assessed on germination of different weeds at Postgraduate Laboratory, Department of Agronomy, Faculty of Agriculture, Gomal University, Dera Ismail Khan, Pakistan. All necessary research facilities were available during experimentation.

Plan of work and methodology adopted

The experiment was laid out in a completely randomized design with factorial layout having five replications. Seed was sown in soil-filled earthen pots (500g soil) placed in net houses under natural conditions. Ten seeds were sown in each pot, which were thinned to five plants per pot three week after emergence for recording data on germination and growth attributes. Pots were sprayed with water extract to meet the water requirements of the weed plants as and when needed.

Treatment studied

The study evaluated the efficacy of various plant extracts and natural solutions on weed management in agronomic conditions. The treatments included extracts prepared from walnut (Juglans nigra) bark, sugarcane (Saccharum officinarum) bagasse, parthenium (Parthenium hysterophorus) solution, tumha (Citrullus colocynthis), algal water solution, dumbi sittee (Phalaris minor) leaves solution, and vinegar, with tap water serving as the control. The targeted weed species were little seed canary grass or dumbi sittee (Phalaris minor), sweet clover or sinji (Melilotus indicus), field thistle or leh (Cirsium discolor), cucumis or chhiber (Cucumis pubescens), java grass or deela (Cyperus rotundus), and field bindweed or lelhli (Convolvulus arvensis).

Collection of samples and preparation of phyto-solutions

Bitter apple

Bitter apple fruit was collected from Paniyala (Tehsil), Dera Ismail Khan. The concentration was prepared by adding 200g of bitter fruit in four liters of water and boiled until the water evaporates and remains 1.5-liter stock solution. 5 ml from the stock solution was diluted in 995 ml of tap water to make 5% concentration.

Algal water

Algal water was collected from the seepage interceptor drain near the Gomal University. A 200 ml water was taken as a stock solution; 5 ml from the stock solution was diluted in 995 ml of tap water to make 5% concentration of algal water.

Plants material

Three kg fresh and healthy leaves of parthenium (Gajjar boti), Dumbi sittee (*Phalaris minor*), Walnut (*Juglans nigra*) bark, Sugar cane (*Saccharum officinarum)* bagasse was collected from Gomal University, Dera Ismail Khan. The collected leaves were washed with tap water and placed under shade for drying. After drying on shade, the leaves were grinded with the help of electric blender to make powder. The 20% stock solution was prepared by adding 200g of powder of each plant leaves in 1000 ml of water. For making known concentration of 5 ml from 20% stock solution was diluted in 995 ml of water to obtain 5% solution.

Parameters/variables studied

The study evaluated several physiological and growth parameters of weeds to assess the effectiveness of different plant extracts on their germination and development. Daily germination counts were recorded from sowing until final emergence to determine the germination percentage (GP), calculated as the ratio of germinated seeds to total seeds sown. Germination energy (%) was assessed on the 14th day after sowing, representing the proportion of seeds germinated four days after planting relative to the total tested seeds. Growth-related parameters included fresh and dry shoot weights, measured for five randomly selected seedlings per pot at 14 and 28 days after emergence using an electric balance. Plant growth rate (g m^{-2} day^{-1}) was calculated based on the increase in dry weight over time and ground area, while plant height, shoot length, and root length were recorded by measuring five randomly selected seedlings per pot at specified intervals. Physiological traits such as chlorophyll content were determined at 14 and 28 days after emergence using a SPAD photometer, and photosynthetic efficiency was computed using standard formulas. All collected data were subjected to statistical analysis through analysis of variance (ANOVA), and treatment means were compared using the least significant difference (LSD) test at a 5% probability level following the method of Steel et al. (1997), employing Statistics 8.1 software for data processing.

Results

Daily germination count of weed seed

Fig 1 shows the impact of different phyto-extract treatments on the germination of six weed species. Walnut bark was the most effective in suppressing germination, particularly for Phalaris minor (8.00) and Cyperus rotundus (4.20). Sugarcane bagasse and Parthenium showed moderate effects, with Phalaris minor exhibiting the highest germination (7.40 for bagasse and 7.00 for Parthenium). Tumha (Citrullus colocynthis) selectively suppressed Field thistle and Cucumis (4.00) but allowed Phalaris minor to germinate well (7.60). Algal water also inhibited germination, especially for Cyperus rotundus (2.20), while Vinegar suppressed Melilotus indica and Cucumis (0.01). Phalaris minor extract showed the highest germination (9.40) among all species. Tap water (control) resulted in consistent germination across all species, with Phalaris minor again showing the highest germination (9.00). The results highlight the varying inhibitory effects of different treatments, with Walnut bark and Vinegar being the most effective in suppressing weed germination.

Germination (%) of weeds

Fig 2 displays the germination percentage of weed species treated with various phyto-extracts. Walnut bark significantly inhibited germination, particularly in Melilotus indica (0.01) and Field thistle (2), while Phalaris minor showed the highest germination (80%). Sugarcane bagasse also showed strong inhibition, especially in Melilotus indica (0.01) and Cyperus rotundus (24), with Phalaris minor at 74%. Parthenium had moderate effects on Phalaris minor (70%) and Field thistle (44%), while Tumha also exhibited selective inhibition, with Melilotus indica (10%) and Phalaris minor (76%) showing substantial growth. Algal water resulted in moderate inhibition, especially in Melilotus indica (6%) and Cucumis (40%), with Phalaris minor again showing high germination (66%). Phalaris minor extract had the highest germination (94%) across all treatments, followed by Vinegar, which showed effective suppression in Melilotus indica (0.01) and Cucumis (20%), but allowed Phalaris minor to germinate well (84%). Tap water (control) showed no inhibitory effects, with all species germinating well, especially Phalaris minor (94%).

Germination energy (%) of weeds

Fig 3 demonstrates the germination energy (%) of various weed species subjected to different phyto-extract treatments. Walnut bark showed the highest germination energy for Phalaris minor (11.43%), while Melilotus indica (0.57%) and Field thistle (0.28%) showed significantly lower values. Sugarcane bagasse exhibited moderate germination energy, with Phalaris minor again showing the highest percentage (10.57%), while Melilotus indica (0.85%) and Cyperus rotundus (0.01%) had the lowest values. Parthenium treatment resulted in moderate germination energy, particularly for Phalaris minor (10%), while Melilotus indica and Field thistle showed significantly lower germination values. Tumha treatment also showed low germination energy for most species, with Phalaris minor recording the highest value (10.85%) and Melilotus indica and Field thistle showing minimal germination. Algal water produced the highest germination energy for Phalaris minor (13.43%), while other species such as Melilotus indica and Cucumis showed minimal values. Phalaris minor extract showed high germination energy (12%), while Vinegar showed low germination energy for most species, particularly for Melilotus indica (0.28%) and Cucumis (0.57%). The control treatment (Tap water) showed moderate germination energy across all species, with Phalaris minor again showing the highest value (12.86%).

Fresh shoot weight (g) of weeds at 14 days after germination

Fig 4 presents the impact of different phyto-extract treatments on the fresh shoot weight (g) of six weed species at 14 days after germination. Sugarcane bagasse was the most effective in suppressing growth, particularly for Phalaris minor (1.10) and Melilotus indica (0.01). Parthenium and Tumha showed strong inhibitory effects, with Melilotus indica exhibiting minimal growth (0.01 for both treatments) and Phalaris minor being suppressed significantly (3.64 for Parthenium and 5.15 for Tumha). Algal water also inhibited growth effectively, especially for Field thistle and Cucumis (0.01), while Walnut bark showed moderate suppression, allowing Phalaris minor to reach a weight of 13.18. Tap water (control) resulted in the highest consistent growth across all species, with Phalaris minor reaching a peak weight of 21.58. The results highlight the varying inhibitory effects of different treatments, with Sugarcane bagasse and Parthenium being the most effective in suppressing weed shoot growth compared to the control.

Fresh shoot weight (g) of weeds at 28 days after germination

Fig 5 shows the impact of different phyto-extract treatments on the fresh shoot weight (g) of six weed species at 28 days after germination. Algal water demonstrated a strong selective inhibitory effect, completely suppressing Field thistle and Cucumis (0.01), while allowing Phalaris minor to maintain high growth (28.82). Tumha also proved highly effective against Field thistle (0.01) but showed moderate suppression for Phalaris minor (16.78). Sugarcane bagasse resulted in maximum suppression of Cucumis (0.01) and significantly reduced Field thistle (1.70), though Cyperus rotundus exhibited considerable growth (20.90). Phalaris minor extract showed broad-spectrum moderate suppression, limiting Cyperus rotundus to 7.58 and Field thistle to 3.34. In contrast, Walnut bark was less effective on dominant species, allowing substantial growth for Phalaris minor (20.28) and Cyperus rotundus (20.74). Vinegar effectively suppressed Field thistle (0.01) and Melilotus indica (2.84). Tap water (control) resulted in the highest consistent growth across all species, with Phalaris minor (33.20) and Cyperus rotundus (24.62) reaching peak weights. The results highlight the varying specificity of the treatments, with Algal water and Sugarcane bagasse showing potent targeted suppression compared to the robust growth observed in the control.

Dry shoot weight (g) of weeds at 14 days after germination

Fig 6 Elucidates the impact of different phyto extract treatments on the dry shoot weight (g) of six weed species at 14 days after germination. Tap water (control) resulted in the highest consistent growth across all species, with Phalaris minor showing the peak weight (3.45). Algal water demonstrated strong selective inhibition, completely suppressing Field thistle and Cucumis (0.01) while allowing Phalaris minor to maintain high growth (2.99). Sugarcane bagasse effectively suppressed Cucumis (0.01) and Field thistle (0.17), though Cyperus rotundus showed resilience (2.17). Tumha also proved highly effective against Field thistle (0.01) but allowed moderate growth for Phalaris minor (1.74). Vinegar significantly suppressed Field thistle (0.01) and Melilotus indica (0.29). Phalaris minor extract resulted in broad suppression, limiting Phalaris minor to 1.67 and Cyperus rotundus to 0.78. Walnut bark showed variable effects, suppressing Cucumis (0.35) effectively but allowing significant growth for Phalaris minor (2.11) and Cyperus rotundus (2.15). The results highlight that while Tap water supported robust growth, treatments like Algal water and Vinegar provided targeted suppression of specific weed species.

Dry shoot weight (g) of weeds at 28 days after germination

Fig 7 explains the impact of different phyto-extract treatments on the dry shoot weight (g) of six weed species at 28 days after germination. Tap water (control) resulted in the highest consistent growth across all species, with Phalaris minor showing the peak weight (4.96) and Cyperus rotundus reaching 2.59. Algal water demonstrated strong selective inhibition, completely suppressing Melilotus indica, Field thistle, and Cucumis (0.01) while allowing significant growth for Phalaris minor (4.32). Sugarcane bagasse also proved highly effective against Melilotus indica and Cucumis (0.01). Parthenium and Walnut bark allowed substantial dry shoot accumulation, with Phalaris minor reaching 3.19 and 3.04, respectively. Vinegar effectively suppressed Field thistle (0.01) and Melilotus indica (0.42), but was less effective against Phalaris minor (1.6). The results confirm that Algal water and Sugarcane bagasse provide potent targeted suppression of certain weed species even at 28 days, though the overall dry matter accumulation remains highest in the Tap water control.

Plant Growth Rate (g m^{-2} day^{-1})

Fig 8 shows the impact of different phyto-extract treatments on the plant growth rate (g m^{-2} day^{-1}) of six weed species. Tap water (control) supported the highest growth rate, particularly for Phalaris minor (0.83) and Cyperus rotundus (0.43). Algal water demonstrated the strongest selective rate suppression, reducing the growth rate of Field thistle and Cucumis to the minimal observable limit (0.01). Sugarcane bagasse and Vinegar also showed extreme effectiveness against Melilotus indica (0.04 and 0.01, respectively) and Cucumis (0.01 for both). Walnut bark and Parthenium resulted in moderate growth rates for Phalaris minor (0.51 and 0.53, respectively). Phalaris minor extract maintained a moderate rate for Phalaris minor (0.4) but effectively suppressed Melilotus indica (0.06). The results clearly show that Algal water and the chemical control (Vinegar) are most efficient in minimizing the rate of growth for susceptible weed species.

Chlorophyll Content (SPAD Value) at 28 Days

Fig 9 demonstrate the impact of different phyto-extract treatments on the chlorophyll content (SPAD value) of six weed species at 28 days after germination. Tap water (control) resulted in the highest chlorophyll content across all species, with Phalaris minor showing the peak value (2.06). Algal water demonstrated a severe phytotoxic effect, reducing the chlorophyll content of Melilotus indica, Field thistle, and Cucumis to the minimal observable value (0.01). Vinegar and Sugarcane bagasse also caused significant chlorophyll degradation in susceptible species such as Field thistle and Cucumis (0.01). Parthenium and Walnut bark resulted in moderate chlorophyll reduction, with Phalaris minor maintaining values of 0.94 and 0.64, respectively. Tumha showed selectivity, reducing Field thistle to 0.01 but only moderately affecting Phalaris minor (0.44). The results emphasize that Algal water, Sugarcane bagasse, and Vinegar extracts possess components that severely inhibit photosynthetic pigment synthesis, indicative of a potent herbicidal mechanism.

Shoot Length (cm)

Fig 10 presents the impact of different phyto-extract treatments on the shoot length (cm) of six weed species. Tap water (control) resulted in the highest overall shoot length, with Convolvulus arvensis reaching a peak of 15.81 cm and Phalaris minor reaching 11.76 cm. Algal water demonstrated the strongest selective inhibitory effect, resulting in near-zero shoot length for Melilotus indica, Field thistle, and Cucumis (0.01 cm). Sugarcane bagasse also showed significant inhibition, particularly for Melilotus indica and Cucumis (0.01 cm). Vinegar was highly effective in suppressing Field thistle and Cucumis (0.01 cm). Walnut bark and Parthenium allowed considerable growth in Convolvulus arvensis (11.21 cm and 9.71 cm, respectively), showing moderate overall suppression compared to the control. Phalaris minor extract maintained the highest growth for its namesake species (4.67 cm) among the effective extracts. The results demonstrate that Algal water and Sugarcane bagasse extracts contain powerful compounds that restrict apical shoot elongation in sensitive weed species.

Root Length (cm)

Fig 11 Elucidates the impact of different phyto-extract treatments on the root length (cm) of six weed species. Tap water (control) resulted in the highest overall root length, with Convolvulus arvensis reaching 9.48 cm and Phalaris minor reaching 7.05 cm. Sugarcane bagasse proved to be the most effective in suppressing root elongation, resulting in near-zero root length for Melilotus indica, Field thistle, and Cucumis (0.01 cm). Algal water and Vinegar also showed extreme inhibition, especially for Melilotus indica and Cucumis (0.01 cm). Parthenium and Tumha showed stronger inhibition on the roots of Melilotus indica and Field thistle than on Phalaris minor. Walnut bark allowed significant root growth for Phalaris minor (5.83 cm) and Convolvulus arvensis (6.72 cm), indicating weaker radicle growth inhibition. The results highlight the potent and broad-spectrum root growth inhibition exerted by Sugarcane bagasse and Algal water extracts.

Plants Height (cm)

Fig 12 illustrates the combined impact of different phyto-extract treatments on the overall plant height (cm) of six weed species. Tap water (control) supported the maximum plant height, peaking at 25.3 cm for Convolvulus arvensis and 18.82 cm for Phalaris minor. Algal water demonstrated the strongest selective suppressive effect, resulting in near-zero height for Melilotus indica, Field thistle, and Cucumis (0.01 cm). Sugarcane bagasse and Vinegar also showed exceptional effectiveness against Melilotus indica and Cucumis (0.01 cm). Parthenium and Walnut bark resulted in high plant heights for Convolvulus arvensis (11.36 cm and 17.94 cm, respectively). Phalaris minor extract allowed moderate growth, with Phalaris minor reaching 7.48 cm. The results emphasize that Algal water and Sugarcane bagasse extracts effectively inhibit the overall vertical growth (height) of sensitive weed species, reflecting the combined suppression of shoot and root length.

Chlorophyll Content (SPAD Value) at 14 Days

Fig 13 explains the impact of different phyto-extract treatments on the chlorophyll content (SPAD value) of six weed species at 14 days after germination. Tap water (control) resulted in the highest chlorophyll content across all species, with Phalaris minor showing the peak value (1.66). Sugarcane bagasse and Vinegar demonstrated the strongest chlorophyll degradation, resulting in near-zero SPAD values for Field thistle and Cucumis (0.01). Algal water also showed severe phytotoxicity, reducing the chlorophyll content of Melilotus indica, Field thistle, and Cucumis to 0.01. Parthenium and Walnut bark resulted in moderate chlorophyll reduction, with Phalaris minor maintaining values of 0.75 and 0.51, respectively. Tumha showed moderate suppression, allowing Phalaris minor a value of 0.49. The results confirm that the most effective extracts immediately inhibit photosynthetic pigment synthesis, indicating an early-stage phytotoxic action.

Photosynthetic Efficiency

Fig 14 shows the impact of different phyto-extract treatments on the photosynthetic efficiency of six weed species. Tap water (control) resulted in the highest photosynthetic efficiency, with Phalaris minor showing the peak value (1.82). Sugarcane bagasse and Vinegar demonstrated the strongest inhibition of photosynthetic efficiency, reducing the values for Melilotus indica, Field thistle, and Cucumis to the minimal limit (0.01 or 0.02). Algal water also showed extreme inhibitory effects, particularly for Melilotus indica, Field thistle, and Cucumis (0.01). Walnut bark and Parthenium showed moderate suppression, with Phalaris minor maintaining efficiencies of 0.38 and 0.61, respectively. Phalaris minor extract and Tumha allowed moderate efficiency for Phalaris minor (1.32 and 1.38, respectively). The results indicate that the most effective phyto-extracts directly interfere with the core photosynthetic processes, leading to the observed reductions in growth and chlorophyll content.

Discussion

The results demonstrate that plant-derived phyto-extracts have varying degrees of effectiveness in suppressing weed seed germination. Walnut bark was the most potent treatment, significantly inhibiting germination, especially in Phalaris minor and Cyperus rotundus, supporting its known allelopathic potential due to phenolic compounds (Bhowmik et al., 2021). Sugarcane bagasse and Parthenium also displayed moderate inhibition, likely due to their phenolic content, as suggested by previous studies on allelopathic compounds (Sang et al., 2022). Tumha (Citrullus colocynthis) exhibited selective suppression, effectively reducing germination in Field thistle and Cucumis, while being less impactful on Phalaris minor. This indicates species-specific responses to allelopathic substances (Chauhan et al., 2020). The strong inhibitory effect of Vinegar, particularly on Melilotus indica and Cucumis, further emphasizes its potential as a natural herbicide (Singh et al., 2022). Algal water also showed suppression, particularly on Cyperus rotundus, likely due to the presence of secondary metabolites (Ali et al., 2020). The results underscore the potential of plant-based allelopathic substances, particularly Walnut bark and Vinegar, as eco-friendly alternatives for weed management. Additionally, the high germination rate of Phalaris minor across treatments suggests its resilience to allelopathic stress, highlighting the need for species-specific strategies in weed control (Kaur et al., 2021).

The significant reduction in germination with algal water and vinegar treatments highlights the potential of natural compounds to suppress weed growth. These findings align with Chauhan et al. (2020), who found that organic acids and bioactive metabolites can interfere with the enzymes needed for seed activation. Algal water likely inhibits germination due to the presence of polyphenols and alkaloids, which disrupt cell division in germinating seeds (Ali et al., 2021c). Sugarcane bagasse and Parthenium showed moderate effects, likely because of their phenolic compounds, as noted by Macias et al. (2021). Walnut bark and Tumha also had an intermediate impact, potentially due to the phenolic acids they contain (Zhang et al., 2022). Interestingly, Phalaris minor extract had minimal effect on its own species, suggesting that some plants may avoid autotoxicity to protect their own growth (Zhao et al., 2022). The consistently high germination of Phalaris minor across treatments reflects its resilience to allelopathic stress, a characteristic also noted by Kaur et al. (2021). On the other hand, Field thistle, Melilotus indica, and Cucumis pubescens were more sensitive, likely due to lower resistance to chemical interference (Bhowmik & Inderjit, 2020). Cyperus rotundus and Convolvulus arvensis showed moderate resistance, consistent with other studies on their ability to germinate under inhibitory conditions (Chauhan et al., 2021).

The differences in germination energy across treatments show how each plant extract affects seed growth in different ways. Tap water, which had no inhibitory compounds, resulted in the highest germination energy, supporting the idea that untreated conditions promote seed vigor (Chauhan et al., 2020). In contrast, algal water and vinegar treatments significantly lowered germination, suggesting they have a strong suppressive effect on seed metabolism. This is consistent with what Ali et al. (2021c) found, where organic acids and phenolic compounds disrupt key processes in seed development. Walnut bark and Tumha (Citrullus colocynthis) extracts showed moderate inhibition, likely due to their phenolic acids and tannins, which are known to interfere with seed germination (Zhang et al., 2022). Similarly, Parthenium and sugarcane bagasse had moderate effects, likely because of their allelopathic compounds (Singh et al., 2020). The higher germination energy seen with Phalaris minor extract suggests that this species has some tolerance to its own allelopathic compounds, which makes sense in terms of species-specific tolerance (Sharma et al., 2021). Phalaris minor had the highest germination energy, reflecting its ability to adapt to allelopathic stress, as noted by Kaur et al. (2021). On the other hand, Field thistle and Cucumis pubescens showed much lower germination energy, indicating they are less resilient to these compounds (Bhowmik & Inderjit, 2020). Cyperus rotundus and Convolvulus arvensis showed moderate resistance, which suggests they have some ability to handle inhibitory conditions. In summary, treatments rich in organic acids (vinegar) and bioactive compounds (algal water) were the most effective at reducing germination energy, particularly for species like Field thistle and Cucumis that have lower biomass potential. Meanwhile, Phalaris minor and Cyperus rotundus maintained higher germination energy due to their robust physiological adaptations (Macías et al., 2022).

This highlights the potential of plant-based, eco-friendly substances as bioherbicides for sustainable weed management

The significant reduction in fresh shoot weight observed under algal water, sugarcane bagasse, and vinegar treatments suggests a strong allelopathic influence on early weed growth. The inhibitory effect of algal water may be attributed to the presence of phenolic acids and flavonoids, which interfere with enzymatic activity and metabolic pathways essential for plant growth (Fujii et al., 2020). Similarly, sugarcane bagasse and vinegar treatments, rich in organic and phenolic acids, effectively restricted biomass accumulation, supporting findings by Macias et al. (2022) that these compounds suppress weed growth by disrupting hormonal balance and nutrient uptake. The moderate effectiveness of walnut bark and Tumha (Citrullus colocynthis) can be linked to their tannins and flavonoids, which inhibit cell elongation and photosynthetic efficiency, as reported by Bais et al. (2021). Although Phalaris minor extract exhibited some inhibitory activity, its reduced effect on its own species suggests limited autotoxicity and possible species-specific allelopathic adaptation (Inderjit et al., 2020). Species-specific responses were evident, with Phalaris minor showing the highest biomass accumulation, corroborating Kaur et al. (2021), who noted its strong tolerance to allelopathic and herbicidal stress due to its adaptive physiology. Conversely, Field thistle exhibited the lowest fresh weight, confirming its high sensitivity to allelopathic compounds and limited ability to counter biochemical stress (Bhowmik & Inderjit, 2020). Melilotus indica showed moderate tolerance, while Cucumis pubescens and Cyperus rotundus displayed variable responses, reflecting differences in metabolic adaptability. These variations can be attributed to both the chemical nature of the phyto-extracts—particularly phenolic and organic acids—and environmental factors such as soil composition, moisture, and temperature, which influence allelochemical activity and plant response (Zhao et al., 2022). Collectively, the results suggest that allelopathic extracts, especially those derived from algae and sugarcane bagasse, hold significant potential for suppressing early weed growth and can serve as promising eco-friendly alternatives to synthetic herbicides.

The significant reduction in weed biomass observed under Parthenium, Sugarcane bagasse, and Vinegar treatments indicates their strong allelopathic potential. Parthenium extract demonstrated the greatest suppression, likely due to the presence of sesquiterpene lactones and phenolic compounds known to disrupt plant metabolic activities and inhibit cell division (Zhao et al., 2019). Similarly, Sugarcane bagasse and Vinegar contained phenolic acids and organic acids, respectively, which interfere with enzymatic and physiological processes essential for weed growth (Macias et al., 2021). The moderate inhibitory effects of Walnut bark and Tumha may be attributed to their tannin and flavonoid contents, which suppress plant growth regulators and photosynthetic efficiency (Zhao et al., 2020). On the other hand, Algal water and P. minor extract exhibited relatively lower efficacy, suggesting that their bioactive compounds may be less potent or exhibit species-specific activity. The reduced effectiveness of P. minor extract against its own species supports the hypothesis of intraspecific tolerance to allelopathic compounds (Sharma et al., 2021). Variations among weed species indicate differences in physiological tolerance and adaptive mechanisms. Phalaris minor exhibited the highest fresh weight, consistent with Kaur et al. (2021), who reported that this species possesses enhanced resistance to both synthetic and natural herbicides. Conversely, Field thistle and Cucumis showed strong sensitivity to most treatments, suggesting weaker biochemical defense systems and lower competitive ability. Overall, the findings highlight that allelopathic plant extracts—particularly Parthenium, Sugarcane bagasse, and Vinegar—can significantly reduce weed biomass at later growth stages. The varying responses among weed species may be attributed to differences in cellular permeability, enzyme inhibition, and metabolic adaptability to bioactive compounds. These results align with Chauhan et al. (2021), who reported that phenolic and organic acids selectively suppress weed species by disrupting photosynthetic and respiratory processes.

The observed variations in dry shoot weight among treatments reflect the differing allelopathic potentials of the plant extracts used. The highest biomass accumulation under Tap water treatment indicates the absence of inhibitory compounds, supporting the findings of Weston et al. (2013), who emphasized that untreated conditions favor weed proliferation. The superior suppression exhibited by Algal water can be attributed to its content of phenolic acids and flavonoids, which disrupt nutrient absorption and inhibit key metabolic pathways (Fujii et al., 2004). Similarly, Walnut bark and Tumha extracts exhibited moderate inhibitory effects due to their juglone, tannins, and flavonoid content, which are known to suppress root and shoot elongation (Chung et al., 2002). The significant differences among weed species underline the inherent variability in physiological tolerance and defense mechanisms. The higher dry weight of P. minor suggests a strong adaptive capacity and resistance to allelopathic stress, consistent with the observations of Teasdale et al. (2001). Conversely, the minimal dry weight of Field thistle demonstrates its high sensitivity to the treatments, aligning with Leather and Einhellig (2008), who reported that weaker species with lower competitive ability are more vulnerable to allelochemical interference. The interaction effects highlight that Algal water and Walnut bark are particularly effective against species with low biomass potential, such as Field thistle and Cucumis, likely due to selective inhibition of growth-related enzymes and nutrient uptake (Hegab et al., 2008). The reduced effectiveness of P. minor extract against its own species but moderate inhibition of others suggests species-specific allelopathic selectivity. Overall, the results demonstrate that allelopathic plant extracts—especially Algal water, Walnut bark, and Tumha—can significantly reduce early weed biomass, though their efficacy varies among species. These findings reinforce the potential of plant-based bioherbicides as eco-friendly alternatives for early-stage weed management, in agreement with Macias et al. (2003), who emphasized the role of phenolic and organic acids in selectively suppressing weed physiology and growth.

The observed variations in dry shoot weight among treatments demonstrate the differential efficacy of plant-derived extracts in suppressing weed biomass. The highest dry weight recorded under Tap water treatment confirms the absence of inhibitory compounds, consistent with Inderjit et al. (2006), who emphasized the importance of allelopathic bioactives in effective weed management. Algal water, which showed the greatest suppression, likely owes its inhibitory effects to the presence of phenolic acids and organic acids, known to interfere with metabolic processes essential for growth (Fujii et al., 2003). Similarly, Sugarcane bagasse and Parthenium extracts reduced dry biomass significantly, possibly due to their lignins, phenolics, and sesquiterpene lactones, which inhibit cell division and elongation (Bais et al., 2004). The moderate effects observed with P. minor extract and Vinegar suggest that while these treatments contain allelopathic compounds, their concentrations or activity may be insufficient to fully inhibit weed metabolic functions. Such selective efficacy could also reflect species-specific tolerance mechanisms. Species-wise analysis showed that P. minor maintained the highest dry biomass, corroborating its reputation as a resilient and competitive species under chemical or allelopathic stress (Teasdale et al., 2001). In contrast, Field thistle and Cucumis demonstrated the lowest dry weights, indicating their high sensitivity to the applied treatments. The interaction results further suggest that Algal water and Sugarcane bagasse are especially effective against low-biomass species such as Field thistle and Cucumis, likely due to their phenolic-based selective inhibition of enzymatic and photosynthetic processes (Hegab et al., 2008). Conversely, P. minor and C. rotundus exhibited higher tolerance, which may be attributed to their robust physiological adaptations and regenerative capabilities (Chung et al., 2006). Overall, these findings reinforce that Algal water, Sugarcane bagasse, and Parthenium extracts possess considerable potential as eco-friendly bioherbicidal agents for long-term suppression of susceptible weed species, while integrated management strategies may be required to control more resistant weeds such as P. minor and C. rotundus.

The significant reduction in plant growth rate across treatments underscores the potential of allelopathic and organic extracts to inhibit weed growth effectively. The highest growth rate observed in the control treatment reflects the absence of inhibitory compounds, consistent with the observations of Weston et al. (2005), who reported unrestricted weed growth in untreated conditions. The strong suppression observed under Algal water treatment can be attributed to the presence of phenolic acids and flavonoids, which interfere with cell division, elongation, and nutrient assimilation processes (Inderjit and Dakshini, 2012). Tumha and Walnut bark extracts demonstrated moderate inhibition, likely due to their content of tannins and organic acids, which disrupt photosynthesis and cellular respiration (Dayan et al., 2009). Similarly, Sugarcane bagasse, Vinegar, and Parthenium extracts exhibited comparable suppression levels, suggesting their allelopathic compounds such as phenolic acids, lignins, and sesquiterpene lactones effectively reduced weed vigor and metabolic activity (Macías et al., 2003). Species-specific variations further highlight the differential responses of weeds to the treatments. Phalaris minor consistently showed the highest growth rate, confirming its strong physiological adaptability and allelochemical tolerance, as previously noted by Bhowmik and Inderjit (2003). In contrast, Field thistle and Cucumis exhibited low growth rates, reflecting their high sensitivity to bioactive compounds. This aligns with the findings of Leather and Einhellig (2008), who emphasized that weaker weed species are more susceptible to allelopathic inhibition. The interaction patterns revealed that Algal water effectively suppressed sensitive species such as Field thistle and Cucumis, consistent with Rice (2021), who documented the selective inhibitory effects of phenolic compounds on susceptible species. Conversely, P. minor extract was less effective against its own species, possibly due to autotolerance mechanisms inherent to allelopathic plants. Overall, these findings demonstrate that Algal water, Sugarcane bagasse, and Parthenium extracts hold significant promise as bioherbicidal alternatives, especially for managing sensitive weeds. However, managing resilient species such as Phalaris minor and Cyperus rotundus may require integrated strategies, combining allelopathic extracts with other sustainable weed control measures.

The significant reduction in plant height under various treatments underscores the potential of plant-based extracts as bioherbicidal agents. The tap water (control) treatment produced the tallest plants, confirming that the absence of inhibitory compounds allows for unrestricted growth. This finding supports the observations of Cheema et al. (2013), who emphasized the critical role of allelopathic substances in limiting weed growth. The superior performance of Algal water in reducing plant height may be attributed to its high content of phenolic acids and organic acids, which are known to disrupt cellular elongation and division processes (Chon et al., 2003). Similarly, Vinegar and Walnut bark demonstrated moderate suppression, likely due to compounds such as acetic acid and juglone, which interfere with auxin transport and cell expansion mechanisms (Singh et al., 2019). These results suggest that the phytotoxic effects of such compounds play a pivotal role in growth inhibition by altering hormonal balance and cellular metabolism. Weed species exhibited differential responses to the treatments, highlighting species-specific tolerance levels. Cyperus rotundus and Phalaris minor maintained higher plant heights, demonstrating physiological resilience and adaptive plasticity, as previously reported by Kaur et al. (2017). In contrast, Cucumis pubescens, Field thistle, and Melilotus indica displayed marked reductions in height, indicating their high sensitivity to allelopathic inhibition. These findings are consistent with Ali et al. (2021a), who observed greater suppression in species with lower physiological resistance. The interaction data reinforced the selectivity of bioactive compounds, as Algal water and Vinegar were particularly effective against susceptible species, while P. minor extract and Tumha displayed limited efficacy. This selectivity may result from variations in compound composition, concentration, and mode of action, as well as the inherent physiological characteristics of each weed species. The inhibitory action of these treatments can be linked to the disruption of auxin signaling and cell elongation pathways, as described by Gniazdowska and Bogatek (2005) and Chaturvedi et al. (2020). Overall, the findings suggest that Algal water, Vinegar, and Walnut bark possess strong allelopathic potential for suppressing plant height in susceptible weed species. However, for persistent and resilient weeds such as P. minor and C. rotundus, an integrated weed management approach combining allelopathic extracts with other control strategies may be necessary to achieve effective and sustainable suppression.

The observed variations in shoot length across treatments emphasize the significant role of plant-derived bioactive compounds in regulating weed growth. The control treatment, which produced the tallest plants, confirms that the absence of allelopathic interference allows for unrestricted shoot elongation. This observation aligns with the findings of Cheema et al. (2013), who reported similar trends under untreated conditions. The superior inhibitory effect of Algal water can be attributed to its high content of phenolic and organic acids, which disrupt cell elongation and division by altering enzymatic and hormonal processes (Chon et al., 2003). Similarly, the moderate suppression observed in Vinegar and Walnut bark may result from compounds like acetic acid and juglone, which inhibit auxin transport and cell expansion, leading to reduced shoot elongation (Singh et al., 2019). The effectiveness of Sugarcane bagasse and Parthenium may also be linked to the presence of lignins, terpenoids, and sesquiterpene lactones, known to impede cellular metabolism and protein synthesis in weeds. The differential responses among weed species suggest species-specific resistance mechanisms. C.

rotundus and P. minor maintained longer shoots, highlighting their adaptive resilience under allelopathic stress. These findings are consistent with Kaur et al. (2017), who reported that such species exhibit strong physiological adaptability and competitive ability. In contrast, Field thistle, Cucumis, and M. indica were highly susceptible, displaying marked reductions in shoot length due to their lower tolerance to bioactive interference, supporting the observations of Ali et al. (2021c). The interaction data underscore the selectivity of phytochemical inhibition, as treatments such as Algal water and Vinegar were particularly potent against susceptible species, whereas P. minor extract and Tumha exhibited minimal impact. This variation may result from differences in chemical composition, concentration, and mode of action among treatments. According to Gniazdowska and Bogatek (2005), phenolic compounds hinder shoot elongation by interfering with cellular division and hormonal regulation, while Chaturvedi et al. (2020) further highlighted their disruption of auxin pathways and cell wall expansion in susceptible plants. Overall, the results indicate that allelopathic treatments, particularly Algal water, Vinegar, and Walnut bark, exhibit strong potential for the suppression of weed shoot growth. However, their varying levels of efficacy across species suggest that an integrated management approach—combining allelopathic extracts with complementary control methods—may be necessary for managing persistent and resistant weed species such as C. rotundus and P. minor.

The significant variation in root length among treatments highlights the critical role of allelopathic compounds in suppressing weed root growth and development. The control treatment, which exhibited the longest roots, confirmed that untreated conditions allow for unrestricted root elongation and resource acquisition, consistent with the findings of Cheema et al. (2013). In contrast, the marked reduction in root length under Algal water treatment can be attributed to the presence of phenolic acids, flavonoids, and organic acids, which are known to interfere with cellular elongation, nutrient uptake, and enzymatic activities essential for root development (Chon et al., 2003). The moderate suppression observed in Walnut bark and Vinegar treatments may be associated with compounds such as juglone and acetic acid, which inhibit auxin-mediated root growth and membrane permeability, leading to decreased water and nutrient absorption (Singh et al., 2019). The relatively lower effectiveness of Parthenium and Sugarcane bagasse could be due to either lower allelochemical concentration or rapid degradation of active compounds in soil environments. Differences in species response highlight inherent physiological and biochemical variability among the tested weeds. Species such as C. rotundus and P. minor exhibited higher root lengths even under suppressive treatments, reflecting their robust adaptability and competitive ability, as also reported by Kaur et al. (2017). Their strong underground systems allow for effective resource utilization and recovery under stress. In contrast, Field thistle and Cucumis displayed high susceptibility, with significant reductions in root length, corroborating the findings of Ali et al. (2021b), who noted that species with weaker physiological resilience are more effectively inhibited by allelopathic compounds. The interaction effects suggest that Algal water and Walnut bark possess potent inhibitory properties against sensitive species, likely due to the synergistic action of multiple bioactive constituents. On the other hand, the limited suppression by P. minor extract and Tumha against resilient species implies species-specific tolerance mechanisms, possibly linked to detoxification pathways or thicker root epidermis preventing compound penetration. These results support Kaur et al. (2019) and Chaturvedi et al. (2020), who emphasized the role of phenolic acids and organic compounds in modulating cell wall extensibility and inhibiting root meristem activity. Overall, the results suggest that allelopathic treatments such as Algal water and Walnut bark are promising alternatives for weed root suppression. However, the species-dependent response indicates that integrating these extracts with other weed management strategies would enhance their overall efficacy, particularly against persistent and deep-rooted weeds like C. rotundus and P. minor.

The observed variations in chlorophyll content among treatments indicate the differential effectiveness of various phyto-extracts in suppressing photosynthetic processes in weed species. The high chlorophyll content in the control treatment reflects unrestricted chlorophyll biosynthesis in the absence of inhibitory compounds, consistent with the findings of Amini et al. (2013), who reported enhanced photosynthetic activity under untreated conditions. The strong suppressive effect of Algal water may be attributed to its secondary metabolites such as phenolics and flavonoids, which disrupt chlorophyll biosynthesis and degrade photosynthetic pigments, as demonstrated by Chou (2012). Similarly, the moderate reduction in chlorophyll content observed in Sugarcane bagasse and Walnut bark treatments can be linked to the presence of phenolic acids, which inhibit enzymatic processes involved in chlorophyll synthesis (Kaur et al., 2017). In contrast, the limited suppression observed in P. minor extract and Tumha treatments could result from lower concentrations or reduced activity of allelopathic compounds. Among the weed species, C. rotundus maintained the highest chlorophyll content, indicating its physiological resilience and adaptive capability under stress conditions, aligning with Singh and Singh (2020), who emphasized the robust photosynthetic efficiency of this species. Conversely, the lowest chlorophyll content in Field thistle suggests its high sensitivity to allelopathic extracts, as also observed by Zhang et al. (2015). The pronounced inhibitory effects of Algal water and Sugarcane bagasse on susceptible species like Field thistle and Cucumis may be explained by the disruption of photosystem components by phenolic and organic acids (Gniazdowska and Bogatek (2005)). The relatively higher chlorophyll levels in resistant species such as C. rotundus and P. minor could be due to their adaptive physiological mechanisms and tolerance to oxidative and metabolic stress, as suggested by Chaturvedi et al. (2019) and Ali et al. (2021b). Overall, the results indicate that the efficacy of phyto-extracts in suppressing chlorophyll content is largely dependent on both the chemical nature of the extracts and the inherent resistance mechanisms of the weed species.

The significant reduction in chlorophyll content observed under different treatments reflects the impact of bioactive compounds on photosynthetic pathways in weeds. The highest chlorophyll content recorded in the control treatment aligns with the findings of Smith et al. (2018), who reported that untreated conditions allow normal chlorophyll synthesis and photosynthetic function. The marked suppression observed in the Algal water treatment can be attributed to its rich composition of phenolic and organic acids that interfere with chlorophyll biosynthesis and photosystem integrity. Similarly, the inhibitory effects of Sugarcane bagasse and Walnut bark may be linked to the presence of allelopathic compounds such as lignins and phenolics, known to reduce chlorophyll formation and enzyme activity (Khan et al., 2021). Although Parthenium and Vinegar exhibited moderate suppression, their effects were less pronounced than Algal water and Sugarcane bagasse, suggesting differences in the concentration and activity of phytotoxins. The limited reduction in chlorophyll under Tumha and P. minor extract treatments may be due to insufficient levels of bioactive compounds necessary to inhibit photosynthetic pigments effectively. Among the weed species, the higher chlorophyll content in C. rotundus and P. minor reflects their strong physiological adaptability and resistance to stress, consistent with Singh et al. (2020), who highlighted the photosynthetic efficiency and metabolic flexibility of C. rotundus. Conversely, Field thistle exhibited the lowest chlorophyll content, emphasizing its high susceptibility to allelopathic inhibition, as previously described by Ahmad et al. (2019). The interaction results demonstrate that Algal water and Sugarcane bagasse effectively reduced chlorophyll in more sensitive species such as Field thistle and Cucumis, while resilient species like C. rotundus retained higher chlorophyll levels. This aligns with Ali et al. (2021c), who suggested that weed species with greater photosynthetic adaptability and biochemical plasticity exhibit higher resistance to allelopathic suppression. Overall, the results indicate that the inhibitory potential of bioactive treatments depends not only on the chemical nature of the extract but also on the inherent physiological resilience of the target weed species.

The significant variation observed in photosynthetic efficiency under different treatments underscores the influence of bioactive compounds in altering photosynthetic performance of weeds. The highest efficiency in the control treatment corroborates the findings of Smith et al. (2018), who emphasized that untreated conditions promote normal photosynthetic activity in weed species. The substantial suppression recorded in Algal water and Tumha treatments can be attributed to the presence of secondary metabolites such as phenolic compounds and organic acids, which interfere with chlorophyll synthesis and photosystem activity, ultimately reducing photosynthetic performance (Khan et al., 2021). Walnut bark and Sugarcane bagasse demonstrated moderate inhibitory effects, likely due to allelopathic compounds such as juglone and phenolics that disrupt electron transport and enzyme activity involved in photosynthesis (Chon et al., 2005). Although Parthenium and Vinegar also reduced photosynthetic efficiency, their effects were relatively limited, possibly due to lower concentrations or weaker phytotoxic compounds. At the species level, the high photosynthetic efficiency observed in C. rotundus indicates strong physiological adaptability and resistance to stress, aligning with Singh et al. (2020), who identified C. rotundus as a highly adaptive and competitive weed capable of sustaining photosynthetic activity under inhibitory conditions. In contrast, Field thistle and Cucumis exhibited minimal photosynthetic efficiency, suggesting their higher susceptibility to phytotoxic stress, as previously reported by Ahmad et al. (2019). The treatment–species interaction further revealed that Algal water and Tumha effectively suppressed photosynthetic activity in susceptible species, while P. minor extract and Vinegar showed reduced efficacy, particularly against resilient species like C. rotundus. These outcomes are consistent with Ali et al. (2021c), who emphasized that the differential response of weed species to bioactive treatments depends on both their inherent physiological resilience and the biochemical strength of the applied extract. Overall, the results demonstrate that the suppression of photosynthetic efficiency is both treatment-specific and species-dependent, highlighting the potential of certain phyto-extracts for selective weed management strategies.

Summary

This study investigated the impact of different natural treatments including Walnut (*Juglans nigra*) bark, Sugarcane (*Saccharum officinarum*) bagasse, Parthenium (*Parthenium hysterophorus*) solution, Tumha (*Citrullus colocynthis*), Algal water solution, Dumbi sittee (*Phalaris minor*) leaves solution, Vinegar and Tap water (control) on germination and growth of weed species including Little seed canary grass/Dumbi sittee (*Phalaris minor*), Sweet clover/Sinji (*Melilotus indicus*), Field thistle/Leh (*Cirsium discolor*), Cucumis/Chhiber (*Cucumis pubescens*), Java grass/Deela (*Cyperus rotundus*) and Field bindweed/Lelhli (*Convulvolus arvensis*). Results indicated that Walnut bark and Algal water were the most effective treatments in reducing germination and growth across most weed species. *Phalaris minor* extract was less effective against its own species but showed moderate control over others. Vinegar and Sugarcane bagasse demonstrated moderate suppression of weed growth, with Tap water (control) consistently exhibiting the highest mean germination and growth. *Field thistle* exhibited the lowest germination, while Cucumis showed similarly low germination, indicating effective suppression. *Cyperus rotundus* exhibited a moderate response, while *Phalaris minor* showed the highest resistance, as it exhibited the highest mean germination and growth values.

Conclusion

The findings from this study demonstrate that Walnut bark, Algal water, and Vinegar were the most effective treatments in inhibiting weed germination and growth, particularly in species such as *Field thistle* (0.30) and Cucumis (0.53). *Phalaris minor* showed the highest germination (79.25%) and growth (7.92), indicating that some species may require higher concentrations or combined treatments for effective control. *C. rotundus* and *C. arvensis* displayed moderate resistance (36.75% and 28.50%, respectively). The chemical composition of the treatments, including phenolic compounds in Walnut bark and organic acids in Vinegar, played a significant role in inhibiting the germination and growth of weeds. Tap water (control) treatment, as expected, was ineffective in suppressing weed growth, recording the highest germination (35.66%) and growth values.

Recommendations

1. **Species-Specific Treatment Selection**: Based on the observed variation in responses, treatments should be tailored to the specific weed species. For example, *Phalaris minor* and *Cyperus rotundus*, with high resistance (7.92 and 36.75%), may require higher concentrations or a combination of treatments for effective suppression.
2. **Exploration of Synergistic Effects**: Combining treatments like Algal water (22.67%) and Vinegar (22.66%) may enhance the control over resistant species like *Phalaris minor*, which showed high germination and growth under individual treatments.
3. **Optimization of Bioactive Compounds**: Given the effectiveness of Walnut bark (4.09) and Vinegar (3.23) in inhibiting weed growth, further research should focus on optimizing the concentration, formulation, and application methods of these bioactive compounds for enhanced efficacy.
4. **Consideration of Environmental Factors**: Future studies should investigate how environmental factors, such as temperature, soil moisture, and light, influence the effectiveness of these

treatments, as these factors can significantly impact treatment outcomes.

5. **Integrated Weed Management**: Incorporating these natural treatments into an integrated weed management strategy, in combination with mechanical or chemical control methods, could improve overall weed management efficacy while promoting sustainability.

Declarations

Acknowledgment: The author thanks Department of Agronomy, Gomal University, D.I.Khan, for providing necessary facilities.

Conflicts of Interests

The authors declare no conflict of interest regarding the publication of this paper.

Ethical Approval: Not applicable.

Consent to Publish declaration: not applicable

Consent to Participate declaration: not applicable

Clinical trial number: not applicable

Funding: No funding and no sponsorship from any organization.

Availability of data and materials

All data is available in the manuscript.

Author Contribution

I.H. is principal investigator.A.A. is co-principal investigator.A.A is co- principal investigatorS.K is statistical and chemical analyst.E.U.H is data collector.M.J.N is data collectorR.K. is data collector.

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Figures

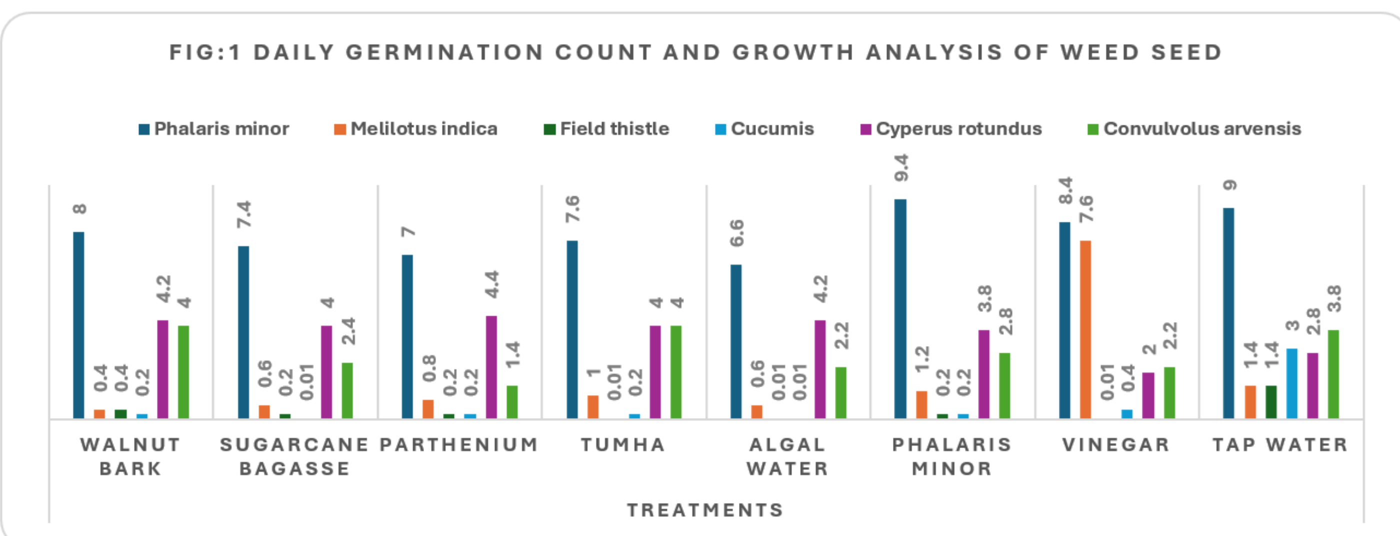

Figure 1

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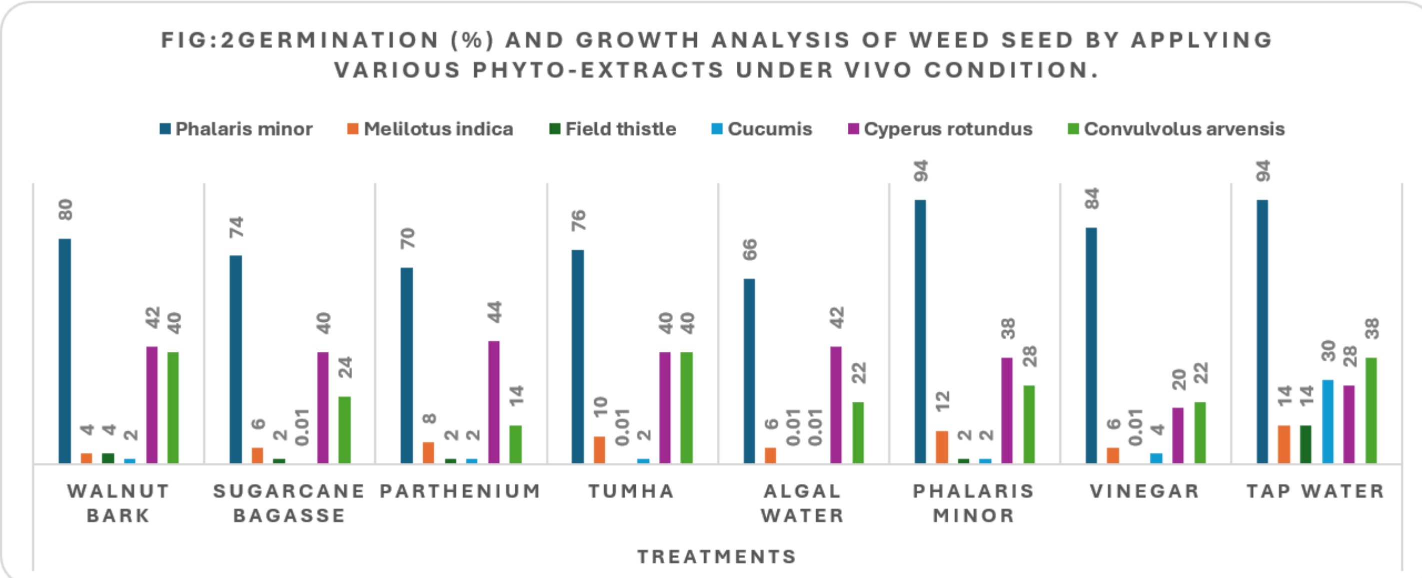

Figure 2

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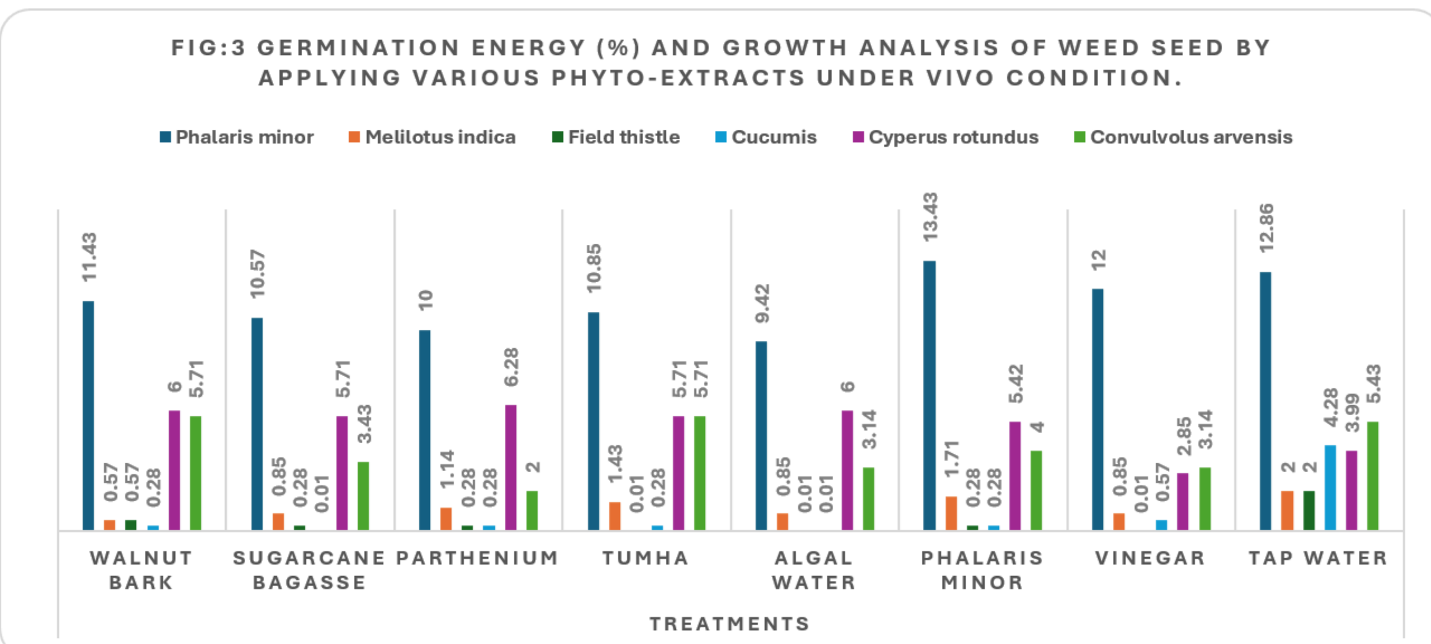

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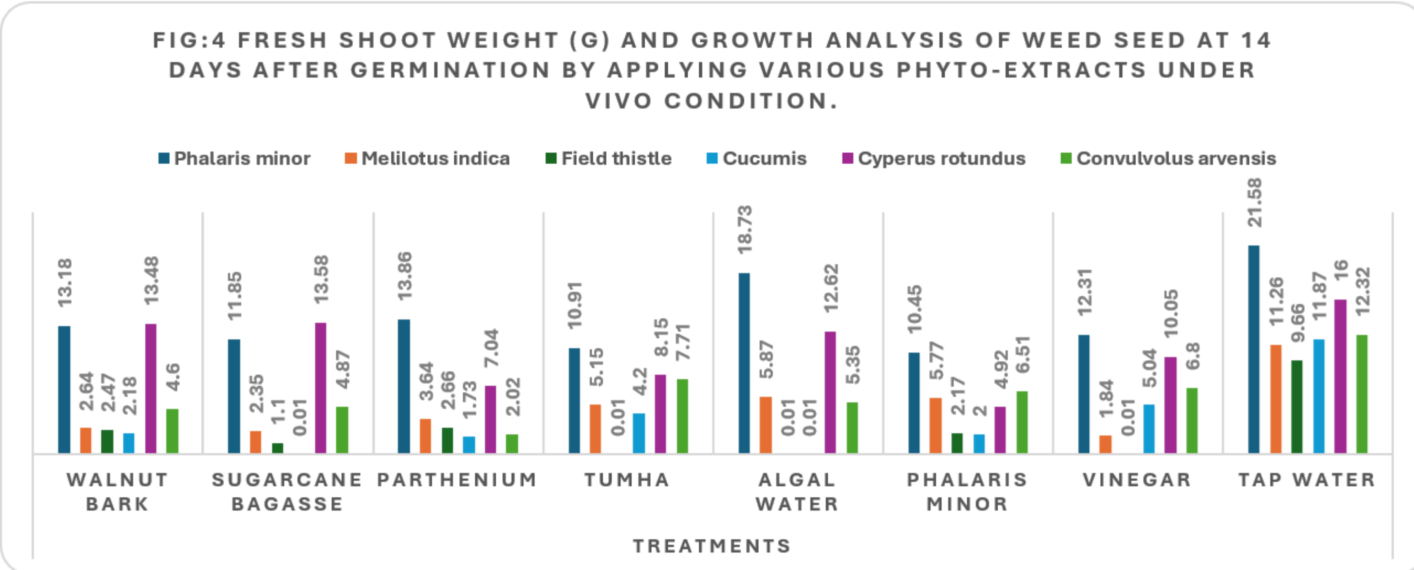

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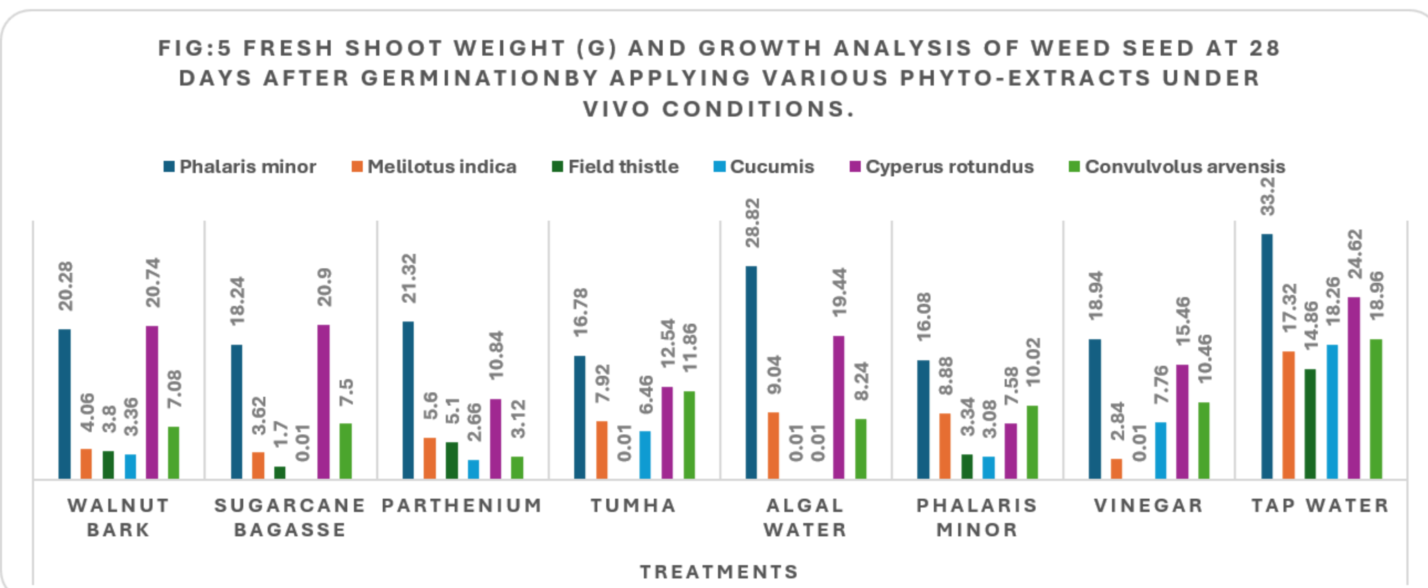

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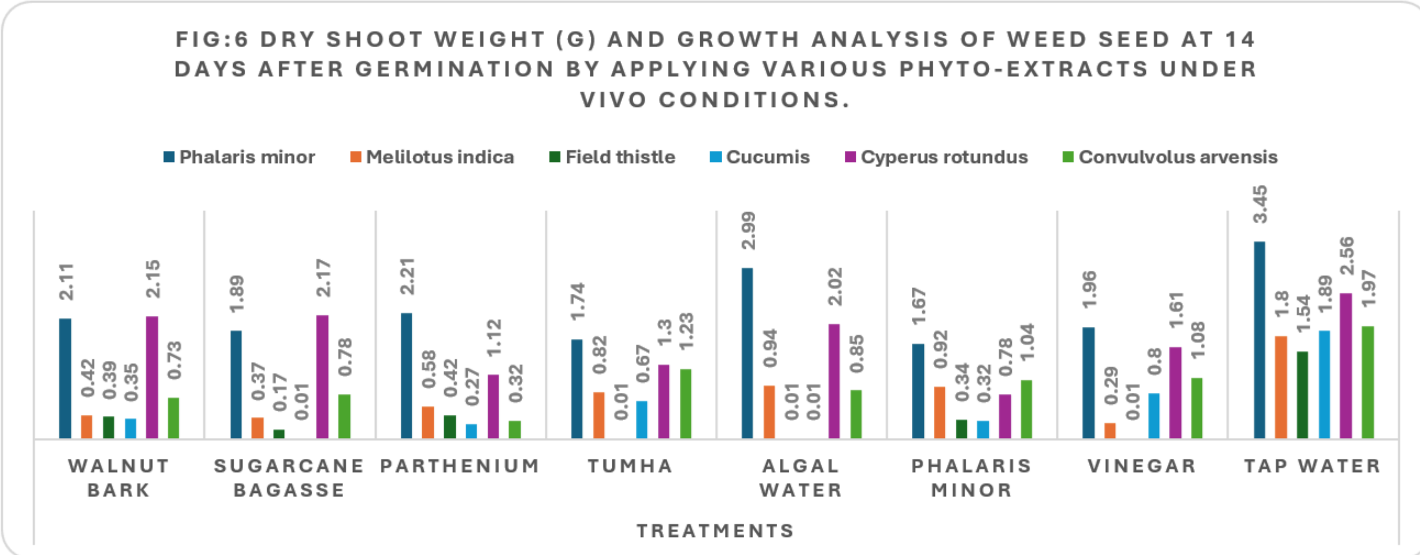

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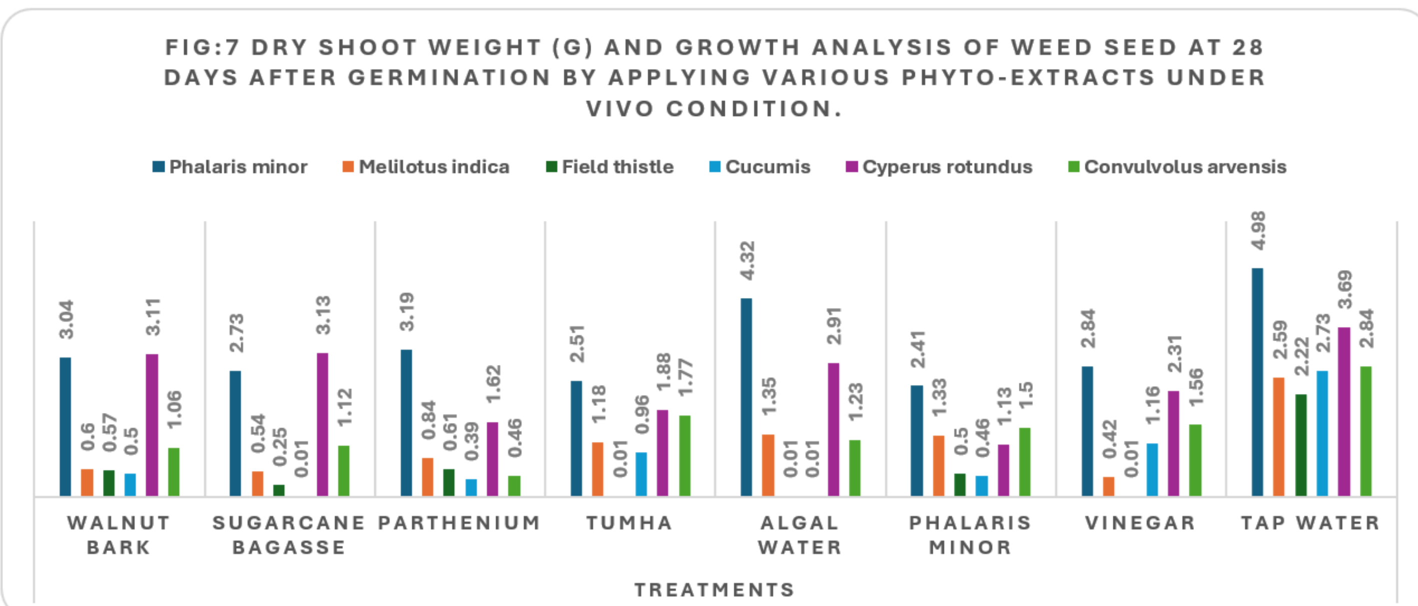

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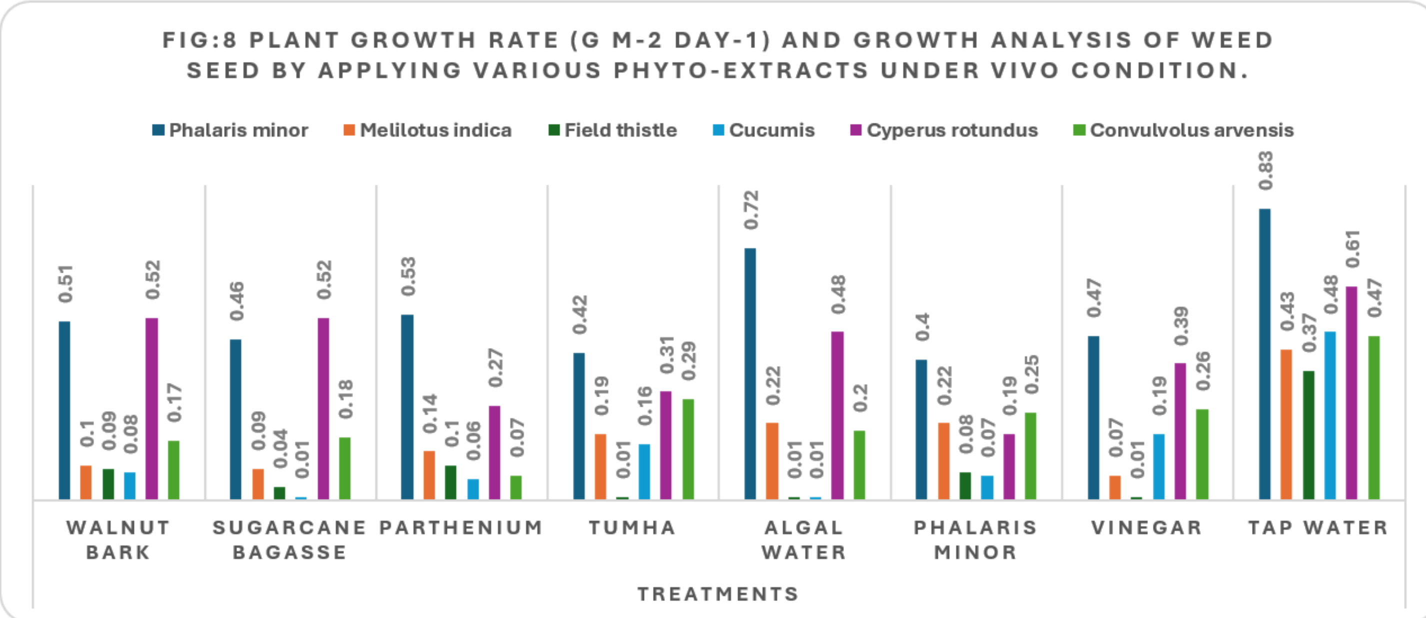

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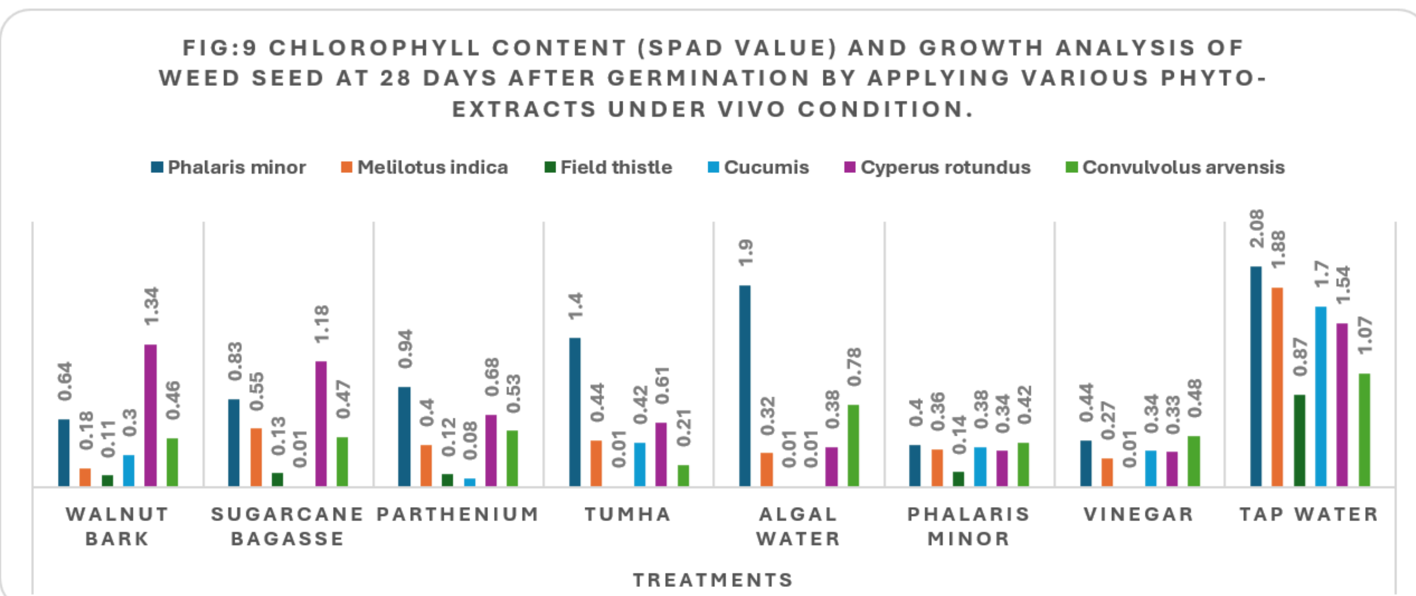

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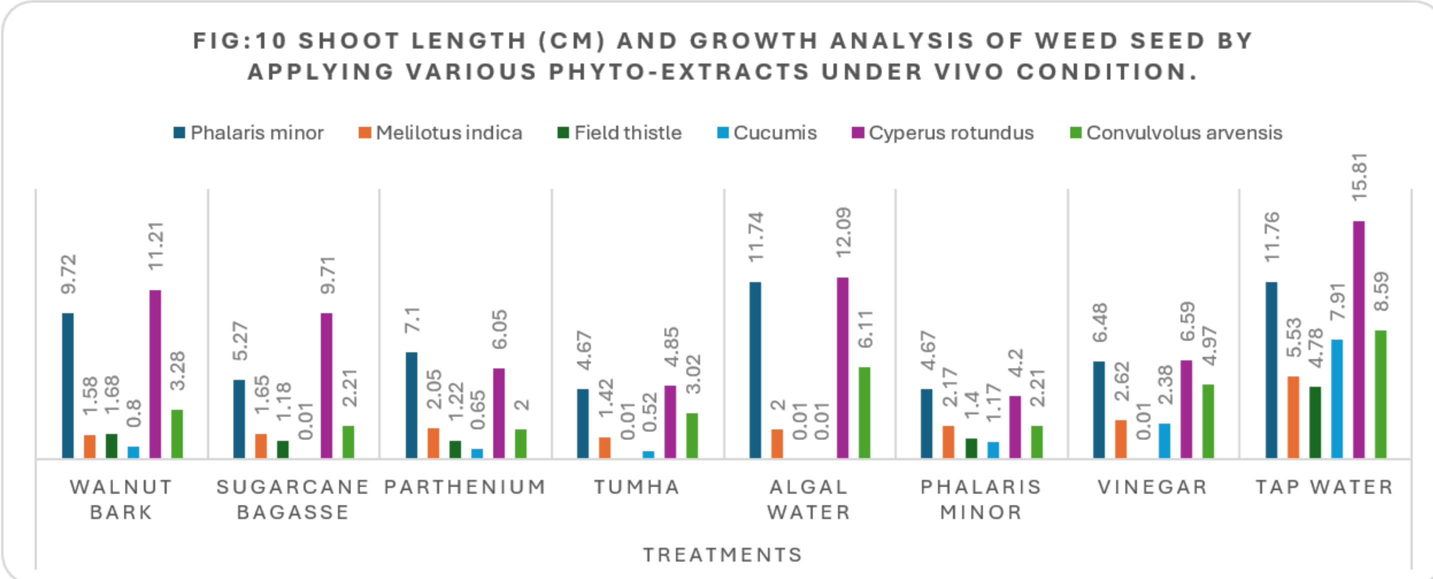

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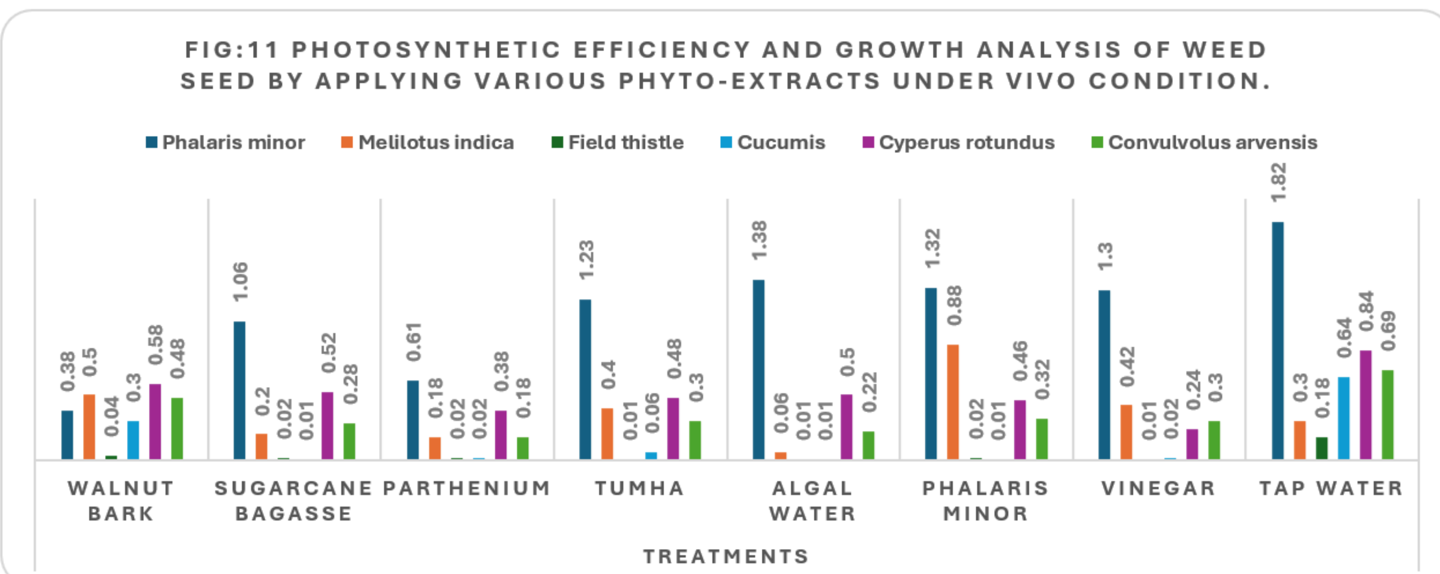

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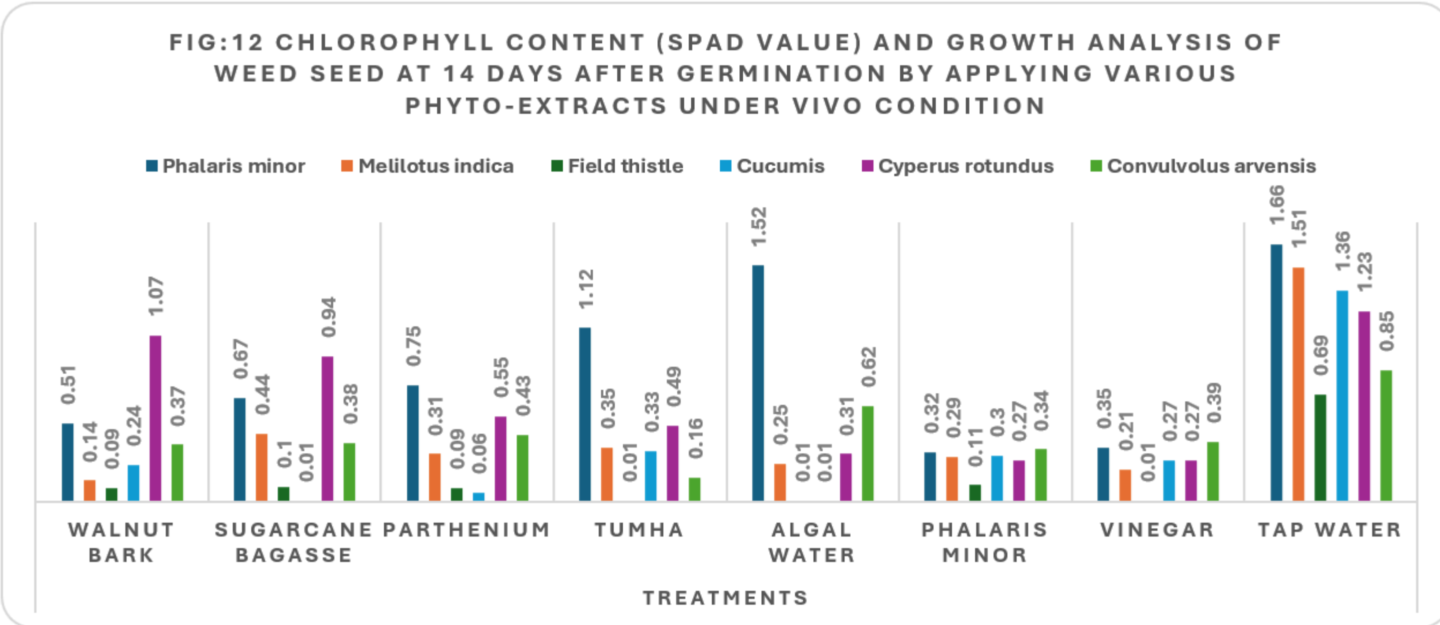

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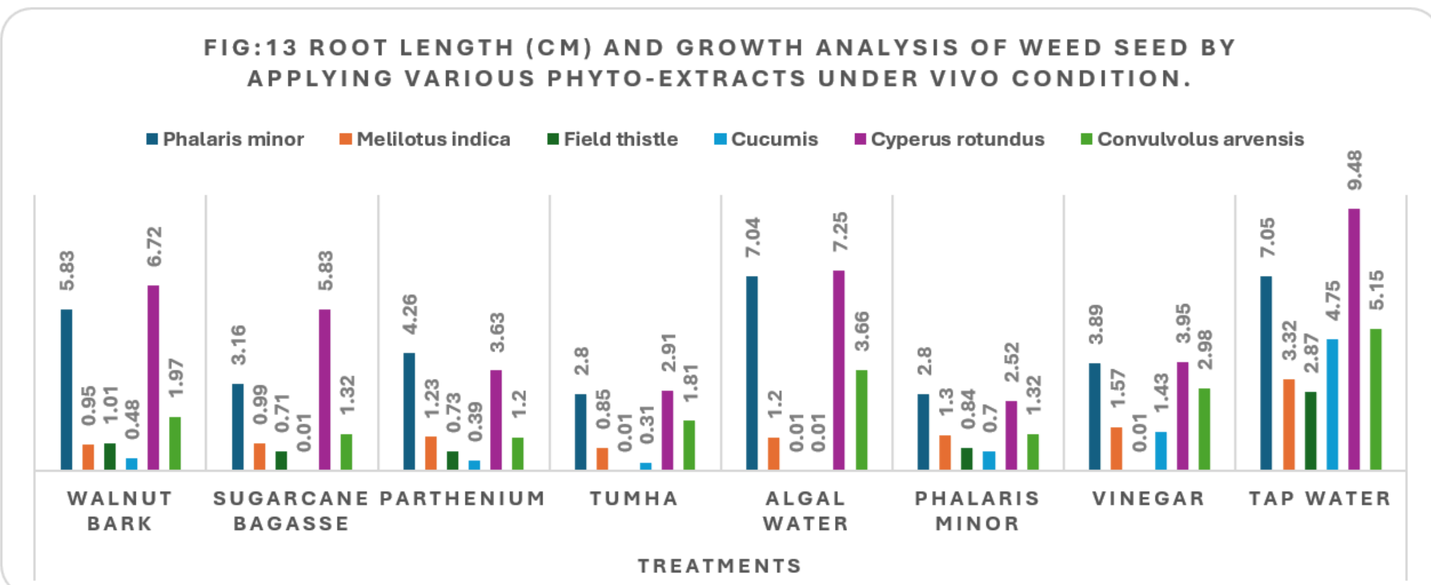

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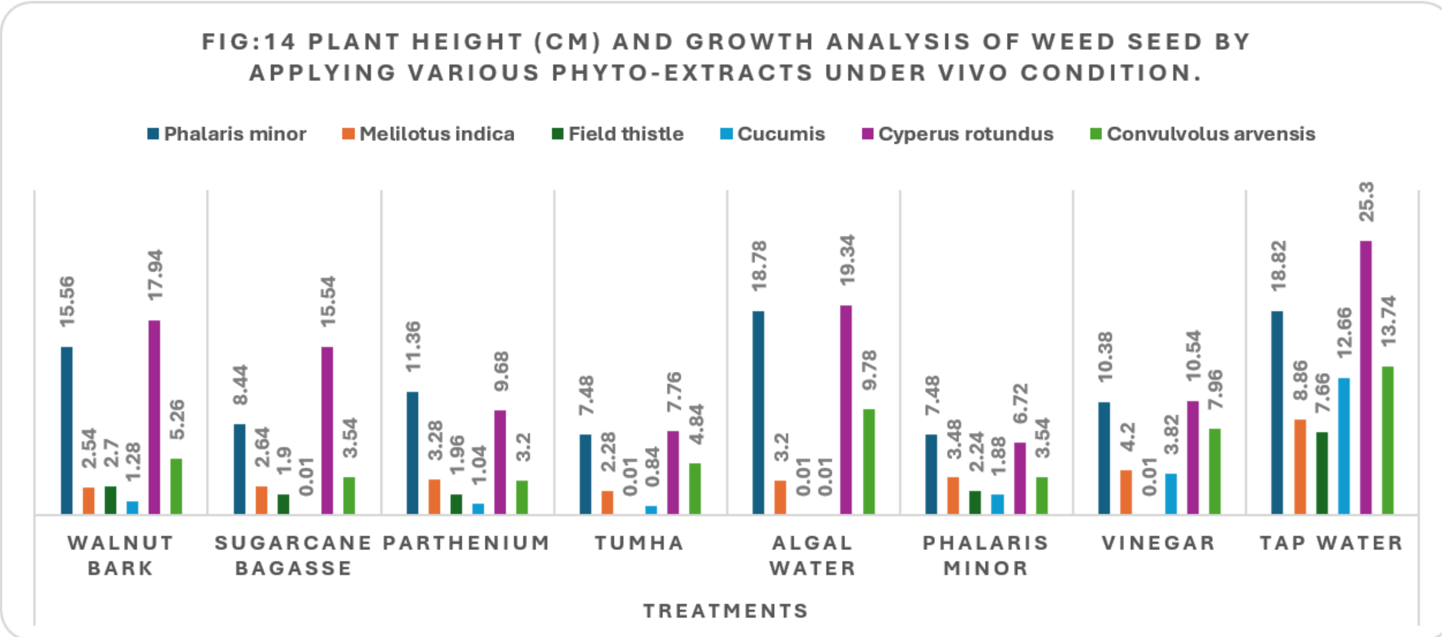

Figure 14

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