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Research Article

Efficacy of Synthetic Herbicides, Organic and Inorganic Mulches, and Allelopathic Extracts for Sustainable Weed Control in Tomato

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Abstract | Weed management plays a crucial role in enhancing tomato yield by minimizing competition for essential resources such as nutrients, water, and sunlight. This study assessed how different weed control techniques affected tomato productivity, growth, and profitability at the Agronomy Research Farm of the University of Agriculture, Peshawar. A field trial was implemented using a Randomized Complete Block Design (RCBD) with three replications and a total of nine treatments. The treatments included the herbicides Percept (haloxyfop-p-methyl) and Pendimethalin, as well as sawdust, black and white plastic mulched, hand weeding twice (at 30 and 60 days after transplantation), extracts of Eucalyptus camaldulensis and Parthenium hysterophorus, and a weedy check. The findings showed that black plastic mulch and manual weeding were the most effective methods in reducing weed density, recording (10.63 m^{-2} and 17.33 m^{-2}), respectively, compared with (52.4 m^{-2}) in the weedy check. Hand weeding also produced the highest fruit yield (14,500 kg ha^{-1}) and fruit weight (2.42 kg $plant^{-1}$), Then mulched with black plastic (13,601 kg ha^{-1}). Among herbicides, Pendimethalin significantly reduced weed competition and achieved the highest cost-benefit ratio (1:4.48), making it the most economically viable option. While allelopathic extracts showed moderate weed suppression, they were less effective than herbicides and mulching. Overall, integrating hand weeding, black plastic mulch, and Pendimethalin offers an effective strategy for optimizing weed control and improving tomato yield while reducing excessive herbicide dependency. Additional studies are required to assess the long-term impacts of various weed management strategies on the health of soil, environmental sustainability, and agricultural productivity.

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Introduction

Tomato (*Lycopersicon esculentum* L.) is a widely cultivated vegetable across the globe and is part of the Solanaceae family. Originally cultivated by Europeans before spreading to indigenous communities, tomatoes have become a key ingredient in diverse cuisines and are often eaten fresh in salads.

As a leading vegetable crop, tomatoes hold the second position in global agricultural significance, trailing only behind potatoes. They are packed with vital nutrients, like carotenoids, lycopene, vitamins C and E, and phenolic compounds, which enhance immune function and may help reduce the risk of chronic diseases like cancer (Janani *et al*., 2025). Tomatoes are enjoyed both raw and cooked and are widely used in food processing to produce items like sauces, juices, soups, sun-dried tomatoes, and ketchup (Okaiyeto *et al*., 2023).

In Pakistan, tomatoes are cultivated on approximately 170.16 thousand acres (68,863 hectares) of farmland, yielding an annual production of 0.763 million tonnes. The country maintains its global rank of 29th in tomato production, with an average yield of 11.1 tonnes per hectare (AMIS, 2025). According to the most recent (FAO, 2024) data, China (45.36 million tonnes) dominates global tomato output, followed by the United States (14.15 million tonnes), India (11.15 million tonnes), Turkey (10.27 million tonnes), and Italy (6.9 million tonnes). Low tomato yields in Pakistan are attributed to multiple factors, including pests, diseases, and environmental variables, with weeds being a major constraint (Khan *et al*., 2023). Weeds compete with crops for essential resources, reducing productivity, quality, and harvest efficiency while increasing production costs. Additionally, weeds serve as habitats for pests and contribute to disease prevalence in tomato crops. Early weed control is crucial, as delayed management severely affects crop yield and quality. Effective weed management strategies can enhance tomato yield and profitability.

Current global assessments estimate that biotic stressors such as insect pests, diseases, and weeds contribute substantially to agricultural production losses, with pests and diseases together causing up to about 40 % of crop yield losses annually, and pests including insects and weeds representing major components of this burden on global food production systems. These figures highlight the continuing challenge that pests and related biotic factors pose to sustainable crop production worldwide (Junaid and Gokce, 2024). Traditional weed control methods in tomato, such as hand weeding and herbicides, can be labor-intensive, costly, and have environmental drawbacks, leading researchers to explore alternative strategies like mulching. Recent field studies and reviews show that mulching whether with plastic films (e.g., black polyethylene) or organic materials (e.g., rice straw, crop residues, or woodchips) can significantly suppress weed emergence and growth by limiting light penetration and creating a physical barrier at the soil surface, which reduces weed density and biomass. In addition to weed suppression, mulches help conserve soil moisture, moderate soil temperatures, and improve tomato yield and quality compared with unmulched controls. For example, studies have found that black plastic mulch greatly reduced weed density and enhanced tomato yield under field conditions, and rice straw mulch consistently provided effective weed suppression and competitive yields in organic tomato systems. These findings highlight mulching as a viable component of integrated weed management in tomato crops worldwide (Singh and Chamroy, 2025; Adamczewska-Sowińska *et al*., 2025; Rahmani *et al*., 2021).

Tomatoes can be grown along with other crops including maize, pepper, okra, and onion (Rana *et al*., 2025). Cultural weed management strategies such as intercropping, cover cropping, and mulch are essential for sustainable agriculture (Singh and Chamroy, 2025). Weed control is a critical component of organic agricultural systems, where the avoidance of synthetic herbicides makes managing weeds essential for maintaining crop productivity and sustainability (Fogliatto *et al*., 2023). Extensive research has explored sustainable weed management strategies, including the implementation of organic and integrated cropping systems that reduce chemical inputs while supporting ecological balance (Singh and Chamroy, 2025). Mulching is particularly beneficial in dryland and water-limited regions like Pakistan because it reduces soil moisture loss by limiting evaporation, maintains more consistent moisture levels, and can reduce irrigation requirements. In addition to conserving water, mulches help moderate soil temperature, support root growth and plant development, make harvesting easier, and have been shown to increase overall crop productivity compared with bare soil conditions (El-Beltagi *et al*., 2023).

Weed competition in tomato crops typically has the greatest impact during the early stages of crop development, particularly within the first 3–6 weeks after transplanting. If weeds are not controlled during this critical period of weed competition, losses in tomato yield can be substantial; recent studies report yield reductions of up to ~58 % under season-long weed interference compared with weed-free conditions, depending on weed species, duration of competition, and growing conditions. The extent of production loss varies with the growth stage of the tomato and the weed flora present, and severe weed interference throughout the season can cause even greater losses. Effective weed management including timely hand weeding, cultural practices, and judicious herbicide use is therefore essential to minimize these losses, but identifying the most efficient and cost-effective approach for specific production systems, such as in Pakistan, remains a key challenge for growers (Laude, 2023; Mohamed, 2023).

While several studies have investigated individual weed management practices such as hand weeding, mulching and herbicide application in tomato, there is limited comparative information on the efficacy and economic feasibility of pendimethalin, haloxypop-p-methyl and allelopathic extracts from Eucalyptus camaldulensis and Parthenium hysterophrous under the local agro-climatic conditions of Peshawar.

This study aims to evaluate the impact of different weed management strategies, such as herbicides, mulching and phytotoxic extracts of plants, on tomato growth and production. It also tries to offer an efficient and cost-effective weed management approach for tomato cultivation.

Materials and Methods

Experimental site and design

The study was carried out at the Agronomy Research Farm of the University of Agriculture in Peshawar. The experiment utilized a Randomized Complete Block Design (RCBD) with three replications. Each replication included nine weed management treatments in a 2 × 3 m^2 plot, totalling 252 m^2 of experimental area. A distance of 1 meter was maintained between replications and 0.5 meters between treatments. In each plot, ten seedlings of the 'Roma' tomato variety were transplanted, positioned on both sides of the ridges. The study evaluated several weed management treatments, including two herbicides: Percept (haloxyfop-p-methyl) applied post-emergence at 0.9 L ha^{-1}, and Pendimethalin applied pre-emergence at 1. 44 L ha^{-1}. Three types of mulches were tested: sawdust, black plastic, and white plastic. Additional treatments included hand weeding performed twice (at 30 and 60 days after transplanting), two plant-based extracts (Eucalyptus camaldulensis L. and Parthenium hysterophorus L., each at 125 g L^{-1}), and an untreated weedy check serving as the control.

Experimental details

A rotavator and cultivator were used to prepare the field, followed by thorough irrigation before transplanting tomato seedlings. The 'Roma' tomato seeds, purchased from a local market, were cultivated into seedlings and transplanted in February 2022. Sawdust mulch was weighed and applied in a 1.0-inch layer two weeks after transplantation. The pre-emergence herbicide (pendimethalin) was applied immediately after transplanting, while post-emergence herbicide was sprayed one month after transplanting. Hand weeding was performed at 30 and 60 days after transplantation (DAT). Fresh leaves of Eucalyptus camaldulensis L. and Parthenium hysterophorus were collected, oven-dried at 65°C for 48 hours, and ground into a fine powder. A 125 g sample of each powdered leaf was soaked in tap water (125 g L^{-1}) for 24 hours. The mixtures were filtered using muslin cloth, and the resulting extracts were stored in labeled bottles for later use. These extracts were applied as post-emergence sprays using a knapsack sprayer. The crop received irrigation as required, along with a standard fertilizer application of 30 kg ha^{-1} potash, 60 kg ha^{-1} phosphorus, and 120 kg ha^{-1} nitrogen. The crop was harvested, and data were recorded on various weed and tomato parameters.

Data collection and statistical analysis

The observed weed parameters included weed density (m^{-2}) was recorded by counting all weeds within a (1m x 1m) quadrat placed randomly in each plot. Fresh weed biomass was determined by uprooting and weighting weeds immediately after sampling, while dry biomass was measured after oven-drying the samples at 65-70 C to constant weight and expressed as (kg ha^{-1}). Days to first flowering were counted from transplanting to the appearance of the first flower. Plant height was measured from the soil surface to the plant apex using a measuring scale. The number of branches and fruits per plant was recorded by manual counting of selected plants. Fruit weight per plant was measured by using a digital balance. Total fruit yield per plot was recorded and converted to kg ha $^{-1}$. The cost-benefit ratio (CBR) was calculated by dividing gross returns by total production costs. The collected data were analyzed using the analysis of variance

(ANOVA) method, appropriate for RCBD, through Statistix software (version 8.1). Treatment means were analyzed using the Least Significant Difference (LSD) test at a 5% significance level, following the method of Steel and Torrie (1980).

Table 1: *Effect of diverse weed control methods on weed density (m^{-2}), fresh and dry weed biomasses (kg ha^{-1}) in tomato crop*

Treatments	Weed density (m^{-2})	Fresh weed biomass (kg ha^{-1})	Dry weed biomass (kg ha^{-1})
Percept (haloxyfop-p-methyl) @ 0.9 L ha^{-1}	23.53 bc	1175.5 bc	402.47 bc
Pendimethalin @ 1.44 L ha^{-1}	21 bc	1019 cd	334.2 cd
Saw Dust Mulch	28.1 b	1348.8 bc	468.97 b
Black Plastic Mulch	17.33 cd	813.1 d	276.9 d
White Plastic Mulch	26.5 b	1166.3 bc	394 bcd
Hand weeding (Twice)	10.63 d	412.1 e	149.17 e
E. Camaldulensis L. extract	26.3 b	1393.9 b	462.27 b
P. Hysterophorus Extract	25.3 b	1315.6 bc	457.4 b
Weedy Check (Control)	52.4 a	2676.8 a	940.5 a
LSD (0.05)	3.59	351.78	122.21
CV%	17.4	16.16	16.35

Results and Discussion

Weed density (m^{-2})

The result revealed that various weed management practices significantly impacted weed density in tomato crops (Table 1). The maximum weed density (52.4 m^{-2}) was recorded in the control plot, while the lowest (10.63 m^{-2}) was noted in hand-weeding plots, followed by black plastic mulch (17.33 m^{-2}). Herbicides pendimethalin and percept resulted in weed densities of 21 and 23 m^{-2}, respectively, showing comparable effectiveness. Sawdust mulch, white plastic mulch, Eucalyptus camaldulensis extract, and Parthenium hysterophorus extract had moderate weed suppression, with densities ranging from 25.3 to 28.1 m^{-2}. Overall, the findings indicate that black plastic mulch and two time hand weeding were the most effective weed control measures, while herbicides provided moderate control. The highest weed population in the weedy check was due to the absence of control measures, allowing unrestricted weed growth. Similar findings have been reported in recent studies, which demonstrated that hand weeding and plastic or organic mulching significantly reduce weed density and improve tomato performance compared to unweeded controls (Daramola *et al*., 2021; Singh and Chamroy, 2025; Mohamed and Abdalla, 2023).

Fresh weed biomass

The results demonstrated that the various weed suppression methods had a substantial ($p \leq 0.05$) impact on fresh weed biomass (Table 1). Hand-weeded plots recorded the minimum fresh weed biomass (412.1 kg ha^{-1}), which was subsequently followed by black plastic mulch (813.1 kg ha^{-1}). Herbicides pendimethalin and percept resulted in fresh weed biomass of 1019 and 1175.5 kg ha^{-1}, respectively, while sawdust mulch, P. hysterophorus, and E. camaldulensis extracts showed moderate suppression, with biomass ranging from 1166.3 to 1348.8 kg ha^{-1}. The highest biomass of fresh weed (1393.9 kg ha^{-1}) was observed in the weedy check plots. The lower biomass of fresh weed in hand-weeded plots resulted from the timely and efficient removal of weeds. Likewise, black plastic mulch restricted weed growth by blocking light and raising soil temperature. These results are similar with Awan *et al.* (2018), who reported that hand weeding significantly reduces weed biomass, while Tarara (2000) found that black plastic mulch effectively blocks radiation and prevents weed emergence.

Dry weed biomass

The data in (Table 1) indicate that hand-weeded plots recorded the lowest dry weed biomass (149.17 kg ha^{-1}), while black plastic mulch also significantly reduced dry weed biomass (276.9 kg ha^{-1}). Herbicides pendimethalin and percept resulted in (334.2 and 402.47 kg ha^{-1}) dry weed biomass, respectively, while sawdust mulch, P. hysterophorus, and E. camaldulensis extracts had moderate effects, ranging from 457.4 to 468.9 kg ha^{-1}. The highest biomass of dry weed (940.5 kg ha^{-1}) was noted in the weedy check. The considerable drop in dry biomass after two hand weedings was attributed to the total eradication of weeds, whereas black plastic mulch reduced weed emergence by restricting light penetration. These findings are consistent with those published by Awan *et al.* (2018) and Yaseen *et al.* (2015), who found that manual weeding by time lowers weed biomass more efficiently than mulching. Similarly, Rajablariani *et al.* (2012) observed a 98% reduction in weed biomass with plastic mulch, while Asaduzzaman (2014) and Imad *et al.* (2021) highlighted the suppressive effects of allelopathic plant extracts on weed growth.

Table 2: *Effect of diverse weed control methods on days to 1st flowering, plant height (cm) and number of branches plant-1 of tomato crop*

Treatments	Days to 1st flowering	Plant height (cm)	Number of branches plant
Percept (haloxyfop-p-methyl) @ 0.9 L ha^{-1}	36.6 abc	77.23 b	8.4 c
Pendimethalin @ 1.44 L ha^{-1}	37.6 a	73.12 c	9.2 b
Saw dust mulch	37.3 ab	78.03 ab	7.3 de
Black plastic mulch	37.6 a	70.68 d	9.7 b
White plastic mulch	37.3 ab	72.36 cd	8.3 c
Hand weeding (Twice)	37.6 a	80.66 a	11.3 a
E. Camaldulensis L. extract	36.6 abc	78.11 ab	7.2 e
P. Hysterophorus Extract	36.3 bc	79.73 ab	8.4 cd
Weedy check (Control)	35.6 c	67.21 e	6.4 f
LSD (0.05)	1.16	2.77	0.69
CV%	1.82	2.14	4.81

Days to first flowering plant^{-1} of tomato

The results showed that different weed management strategies significantly affected the days to first flowering in tomato (Table 2). The longest time to first flowering (37.6 days) was recorded under hand weeding (30 and 60 DAT), Pendimethalin and black plastic mulch, comparable with sawdust and white plastic mulch. The shortest duration (35.6 days) occurred in the weedy check. The variation in flowering time among treatments may be associated with differences in the level of weed competition. Effective weed control treatments were characterized by a relatively delayed flowering, whereas earlier flowering was observed in the weedy check. This pattern is in agreement with findings of Rehman *et al.* (2012), who reported that weed competition can influence flowering behavior in tomato and is often associated with reduced yield.

Plant height (cm)

The results indicated that weed management strategies significantly influenced tomato plant height (Table 2). The tallest plants (80.6 cm) were observed in hand-weeded plots at 30 and 60 DAT, with slightly shorter heights in plots treated with *P. hysterophorus* (79.7 cm) and *E. camaldulensis* extracts (78.1 cm), which were statistically at par with sawdust mulch (78 cm). Percept, Pendimethalin, and black plastic mulch resulted in plant heights of (77.2, 73.1, and 70.6 cm), respectively, while the shortest plants (67.2 cm) were noted in the weedy check. The greater plant height in hand-weeding plots was due to reduced weed competition, ensuring better nutrient and moisture availability. The positive effect of allelopathic extracts on plant height may be attributed to the stimulatory impact of allelochemicals in low concentrations (Imad *et al.*, 2021). Similarly, sawdust mulch improved soil conditions, enhancing plant growth (Agboola *et al.*, 2018). Black plastic mulch also contributed to taller plants by suppressing weeds, increasing soil temperature, and improving growth conditions. These findings align with Gordon *et al.* (2010), who reported taller plants under black plastic mulch compared to white plastic mulch.

Number of branches plant^{-1} of tomato

Weed management significantly affected the number of branches per tomato plant (Table 2). The highest number of branches (11.3) was observed in hand-weeding plots, followed by black plastic mulch (9.7) and pendimethalin (9.2), which did not differ significantly from each other. Moderate branching was observed in Percept (8.4), Parthenium hysterophorus extract (8.4), and white plastic mulch (8.3). Sawdust mulch (7.3) and Eucalyptus camaldulensis extract (7.2) produced fewer branches, while the lowest (6.4) was recorded in the control. Hand weeding at critical intervals reduced competition, enhancing plant growth, while black plastic mulch improved branching by suppressing weeds and improving soil conditions. These findings align with Samih and Abubaker (2013), Ibarra-Jiménez *et al.* (2011), and Ngouajio and Ernest (2004), who reported that mulch promotes tomato branching and overall growth by conserving moisture and nutrients.

Number of fruits plant^{-1}

Weed management treatments had a significant effect on the number of fruits tomato plant^{-1} (Table 3). Hand weeding (27.1) and black plastic mulch (26.2) resulted in the highest number of fruits, showing no significant difference between them. White plastic mulch (23.7) and pendimethalin (23.2) ranked next, also exhibiting statistical similarity. Moderate fruit numbers were observed in Percept (21.3) and sawdust mulch (21.0), followed by Parthenium hysterophorus (19.3) and Eucalyptus camaldulensis (17.7), which were statistically similar. The lowest count (10.1) was recorded in weedy check plots. Hand weeding and plastic mulch were the most effective, with black mulch also conserving soil moisture. These results align with Pinder *et al.* (2016) and Ijaz *et al.* (2017), who recommended black polythene for tomato weed control. While herbicides are effective, their environmental risks highlight the need for sustainable weed management.

Table 3: *Effect of diverse weed control methods on number of fruits plant^{-1}, fruit weight (kg plant^{-1}) and tomato fruit yield (kg ha^{-1}) of tomato*

Treatments	Number of fruits plant^{-1}	Fruits weight (kg plant^{-1})	Fruits yield (kg ha^{-1})
Percept (haloxyfop-p-methyl) @ 0.9 L ha^{-1}	21.3 c	1.92 bc	11534 d
Pendimethalin @ 1.44 L ha^{-1}	23.2 b	2.09 b	12531 c
Saw dust mulch	21.0 c	1.88 c	11258 d
Black plastic mulch	26.2 a	2.32 a	13601 b
White plastic mulch	23.7 b	2.11 b	12640 c
Hand weeding (Twice)	27.1 a	2.42 a	14500 a
E. Camaldulensis L. extract	17.7 d	1.60 d	9600 e
P. Hysterophorus Extract	19.3 d	1.55 d	9947 e
Weedy Check (Control)	10.1 e	0.91 e	5607 f
LSD (0.05)	1.82	0.18	842.2
CV%	5.02	5.76	4.33

Weight of fruit plant^{-1}

The analysis of the data showed that various weed management treatments significantly influenced tomato fruit weight (Table 3). The maximum fruit weight was noted in hand weeding (2.42 kg plant^{-1}) and black plastic mulch (2.34 kg plant^{-1}), which were statistically similar. These were followed by white plastic mulch (2.11 kg plant^{-1}), pendimethalin (2.09 kg plant^{-1}), and Percept (2.11, 2.09 and 1.92 kg plant^{-1}). Moderate fruit weights were observed in sawdust mulch (1.88 kg plant^{-1}), Parthenium hysterophorus extract (1.60 kg plant^{-1}), and Eucalyptus camaldulensis extract (1.55 kg plant^{-1}), while the lowest (0.91 kg plant^{-1}) was recorded in the control. These findings suggest that effective weed management significantly improves fruit weight by reducing competition for nutrients and water. Hand weeding was the most effective strategy, leading to the highest fruit weight, consistent with Awan *et al.* (2018). Black plastic mulch also contributed to increased fruit weight by suppressing weeds, conserving soil moisture, and regulating soil temperature. Similar results were reported by Edgar (2018), who found that weed competition negatively affects tomato fruit weight.

Tomato fruit yield (kg ha^{-1})

The findings from the data analysis demonstrate that tomato production was significantly influenced by different weed management strategies (Table 3). The highest yield (14,500 kg ha^{-1}) was observed in two time hand weeded plots, followed by black plastic mulch (13,601 kg ha^{-1}). White plastic mulch and pendimethalin resulted in comparable yields (12,531 and 12,640 kg ha^{-1}), while sawdust mulch and Percept herbicide produced (11,258 and 11,534 kg ha^{-1}), respectively. P. hysterophorus and E. camaldulensis extracts yielded relatively lower fruit production (9,947 and 9,660 kg ha^{-1}), whereas the minimum yield (5,607 kg ha^{-1}) was recorded in control plots. Hand weeding proved to be the most effective method, significantly reducing weed competition and allowing the crop to allocate more resources to fruit development. Similarly, black plastic mulch suppressed weed growth by limiting light interception, leading to improved yield. Our results are consistent with the findings of Ahmed *et al.* (2020), who reported that black plastic mulch enhances crop productivity by conserving soil moisture and suppressing weed growth. The reduced yield observed in the control plots of our study was likely due to intense weed competition. Similar observations were made by Hannan *et al.* (2012) and Singh *et al.* (2019), who also highlighted the detrimental effects of weeds on tomato yield.

Cost benefit ratio

The economic analysis showed significant variation in CBR among different weed management treatments (Table 4). Pendimethalin recorded the highest CBR of (1:4.48), followed by hand weeding at (1:4.2)7, and Percept herbicide with a CBR (1:4.12). Black plastic mulch resulted in a CBR of (1:3.77), while sawdust mulch, white plastic mulch, and allelopathic extracts had moderate values ranging from (1:3.59 to 1:3.41). The lowest CBR (1:2.09) was noted in the control plots. The finding indicate that effective weed control significantly improves economic returns. Herbicide applications, particularly pendimethalin, provided a high CBR due to their lower cost and efficient weed suppression. Hand weeding and black plastic mulch, though highly effective, had higher input costs, affecting profitability. The findings were in line with Olayinka *et al.* (2017), who examine that pendimethalin and hand weeding decreased infestation of weed and increased net returns. Likewise, Hamid *et al.* (2022) observed that black plastic mulch improved tomato yield, reduced labor costs, and enhanced profitability. The study suggests that pendimethalin, hand weeding, and black plastic mulch are effective weed control strategies for achieving higher economic benefits in tomato production.

Table 4: *Economic evaluation (PKR ha^{-1}) of various weed control treatments in tomato farming*

Treatments	Total cost	Gross income	Net income	CBR
Percept (haloxy-fop-p-methyl) @ 0.9 L ha^{-1}	111700	459754	348054	1: 4.12
Pendimethalin @ 1.44 L ha^{-1}	111825	501231	389406	1: 4.48
Saw dust mulch	125500	450338	324838	1: 3.59
Black plastic mulch	144500	544051	399551	1: 3.77
White plastic mulch	144500	505600	361100	1: 3.50
Hand weeding (Twice)	135900	580000	444100	1: 4.27
E. Camaldulensis L. Extract	112700	384000	271300	1: 3.41
P. Hysterophorus Extract	112700	397867	285167	1: 3.53
Weedy check (Control)	107100	224267	117167	1: 2.09

Conclusions and Recommendations

Effective weed management is essential for optimizing tomato growth, yield, and economic returns. This study demonstrated that two time manual weeding and black plastic mulch were the most successful in suppressing weed density and enhancing fruit yield, making them viable options for sustainable weed control. Among all treatments, pendimethalin proved to be the most cost-effective option, as it significantly reduced weed competition and achieved the highest cost-benefit ratio, directly fulfilling the study objective. While allelopathic extracts exhibited moderate weed suppression, they were less effective than conventional methods.

Integrating mechanical, chemical, and cultural weed control strategies can enhance tomato production while minimizing environmental risks. Black plastic mulch and Pendimethalin offer practical solutions for reducing labor costs and maintaining high yields. However, continuous herbicide use may lead to resistance issues, necessitating further research into sustainable alternatives such as bio-herbicides and integrated weed management systems. Future studies should also focus on the long-term impact of these practices on soil health and ecosystem sustainability.

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Novelty Statement

This study demonstrates that black plastic mulch and pendimethalin are effective, sustainable alternatives to hand weeding for weed suppression and tomato yield improvement.

Author's Contribution

Rashid Anwar: Conducted the primary research, performed field data collection, analyzed the data, and interpreted the results.
Muhammad Saddique: Performed formal statistical analysis using Statistix software, managed the methodology development, provided necessary resources, and reviewed and edited the manuscript.
Muhammad Fawad: Contributed to the experimental design, assisted in the application of herbicide and mulch treatments, and helped in the preparation of allelopathic extracts.
Meher Ali: Assisted in the field experimental setup, aided in the daily data collection of plant parameters, and contributed to the refinement of the manuscript.
Abdus Samad Khan: Supervised the site preparation at the agronomy research farm, provided technical guidance on weed parameters, and performed the final proofreading of the article.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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