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RESEARCH PAPER

Eco-friendly pest management in chilli (*Capsicum annuum* L.) using marigold intercropping and plant-derived sprays

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Key Message: The combined application of marigold (Tagetes spp.) intercropping and plant-derived vegetable extract was the most effective treatment for improving chilli (*Capsicum annuum* L.) growth, reducing insect pest populations and enhancing fruit production. These findings highlight the potential of combining companion planting with botanical sprays as an eco-friendly and sustainable strategy for insect pest management and improved chilli productivity.

Abstract

Chilli pepper (*Capsicum annuum* L.) is an economically important crop cultivated worldwide for its commercial value and nutritional significance. However, its production is adversely affected by insect pests, including whiteflies, thrips, and aphids. Excessive reliance on synthetic pesticides raises concerns regarding human health and environmental sustainability. Therefore, the present study was conducted to evaluate the effectiveness of marigold (Tagetes spp.) intercropping and foliar application of vegetable extract, individually and in combination, for managing insect pests and improving the growth and yield of chilli pepper. The experiment comprised four treatments: T_0 (control), T_1 (marigold intercropping), T_2 (foliar application of vegetable extract), and T_3 (combined application of marigold intercropping and vegetable extract), with three replications. The results demonstrated that T3 performed best across most growth, pest-management, and yield parameters. At 75 days, the maximum plant height of 63.45 cm and the highest number of leaves (183.57 per plant), were recorded in T_3, compared with 45.975 cm in the control. The mean number of damaged leaves was reduced to 3.012 per plant in T_3, compared with 5.50 in T_2 and 6.74 in T_1. The maximum stem diameter (1.74 cm) was recorded in T3, although treatment differences were statistically non-significant. The highest number of flowers, 81.25 per plant, was observed in T_3 at 60 days. Similarly, the mean number of damaged flowers was reduced to 1.41 per plant in T_3. The lowest mean insect population, 1.23 insects per plant, was also recorded in T_3, compared with 2.63 in T_1 and 4.62 in the control. Regarding fruit production, T3 produced a maximum of 64.69 fruits per plant at 75 days, with a mean of 32.26 fruits per plant, compared with 29.29 in T2, 25.67 in T_1, and 18.51 in control. These findings suggest that integrating companion planting with plant-derived extracts can provide a promising component of environmentally sustainable pest management in chilli cultivation. © 2026 The Author(s)

Keywords: Bio-control, Chilli pepper, Marigold, Pest pressure, Plant growth, Vegetables extract

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Introduction

Capsicum annuum L. commonly known as chilli and belongs to family solanaceae, is widely cultivated species which has been used since ancient time as food flavoring agent and for curing human health related issues (Ali et al., 2025). Mexico is considered as a centre for cultivation and genetic diversity for chilli production (López Castilla et al., 2019). In Southern region generally the chilli farming is preferred in gardens, backyard as well as in suitable areas as highly control crop. The first identification of germplasm occurred in Southern part of Mexico and showed a great genetic variation of three species i.e., *Capsicum frutescens* L., *Capsicum annuum,* and *Capsicum chinense* Jacq (Perez et al., 2008; Prado et al., 2008). Chilli consists of 27 varieties, out of these only 5 varieties (*C. annuum* L., *C. chinense* Jacq., *C. frutescens* L., *C. baccatum* L., *C. pubescens*) are mostly cultivated worldwide (Paredes Andrade et al., 2020). Chilli has significant impact on human health and is extensively used in pharmaceutical industry due to their high antioxidant level (Topuz & Ozdemir, 2007; Bal et al., 2022). Chilli fruit comprises of a wide range of cancer prevention agent particularly vitamin A, C & Capsaicin which controls the best variation in fruit's smell, taste and in this way attracts ultimate consumer (Bhattacharya et al., 2010; Akhter et al., 2024). Moreover, the organic products arrangement changes with maturity level, ecological conditions, developed sorts and managing crop (Medina-Lara et al., 2008; Vera-Guzman et al., 2011). More Vitamin C is available in new green chillies than carrots and citrus. It also contains 340 mg of

vitamin A, B, C, E and bioflavonoids which are available in per 100 g of chillies (Marin et al., 2004). Chilli can be utilized in many forms such as spice, condiment, flavors and in various kinds of refined items i.e., Sauces and pickles (Haazra et al., 2011; Ďúranová et al., 2022). *Capsicum annuum* is small shrub which grows up to 2 m tall having white or white bluish coloured flowers usually two or more on each node of the plant (Russo, 2012). The most suitable soil for the cultivation of chilli is well drained loamy soil rich in organic matter and optimum pH for best growth of chilli is 5.5- 7.0 with annual rainfall 600-1250 mm. Temperature ranges between 20-25°C is consider as ideal for chilli cultivation. Yield of chillies may reduce due to salinity that's why it is considered as salt sensitive crop (Navarro et al., 2002).

Chilli is a key vegetable crop extensively used around the globe and holds a large number of shares in world economy due to its excessive culinary usage (Djian-Caporalino et al., 2006; Dias et al., 2013). Top five chilli producing countries are Spain, Turkey, China, Mexico, and Peru while China, Thailand, Peru, India and Pakistan are the top five of dried chilli suppliers in the world nowadays (FAO, 2017). In Pakistan during 2025-26, the yield of chillies was 114,400 tons on area of 49,500 hectares which has been raised by 0.5% in 2024-25 yields up to 113,800 tons on area of 49,000 hectares ("Chili Cultivation," 2025). *Capsicum annuum* L. and *C. frutescens* L. these two species and their several cultivars have established a substantial increase in production in Pakistan moreover, its make them a significant cash crop (Amin et al., 2025). The average production of chillies in Pakistan stays low because of leaf and roots pathogens. Fungi and nematodes play a prominence role in declined production of chillies in our country (Khan et al., 2000; Hussain & Abid, 2011). The decline in pest and pathogen attack in chilli crop is achieved by the application of various types of insecticides (Hussain & Abid, 2011). Also the investigations on control of root knot nematodes related diseases of chillies in Pakistan have been conducted (Zarina & Shahina, 2010). Over the past two decades, chilli production, particularly in irrigated areas, has relied heavily on insecticides for pest management. However, excessive pesticide application can lead to harmful residues in chilli fruits, posing risks to crop quality and consumer health (Amekawa et al., 2023; Shim et al., 2023; Rajpoot et al., 2025). Although chemical pesticides can suppress insect pests, their excessive use may promote pest resistance and harm beneficial natural enemies. Furthermore, pesticide residues can compromise the quality and safety of chilli fruits, limiting their suitability for domestic consumption and international trade. Therefore, reducing reliance on chemical pesticides is essential for producing high-quality, safe, and marketable chillies (Mi & Giao, 2022; Ahmad et al., 2024; Verdadero et al., 2025).

In developing countries due to lack of awareness and knowledge, the use of chemicals for insects and pest control is high which ultimately causes negative effect on human health and ecosystem (Sabran & Abas, 2021; Russu, 2023). The overuse of chemical pesticides causes natural and medical issues that are the point of thinking (Ali, 2023; Ahmad et al., 2024). Toxic effects of chemicals are due to the factors such as time period, quantity and toxicity of chemicals and environmental factors. Altered natural states of the regions are additional factors for intense and persistent harming on human life and on environment (Shetty et al., 2023; Naik et al., 2024). Bio fertilization show positive change against synthetic fertilizers. In environmental point of view bio fertilizers are more secure than synthetic fertilizer (Biswas et al., 2014). The use of synthetic chemical pesticides can adversely affect beneficial natural enemies and pollinators in horticultural fields, disrupting biological pest control and essential pollination services (Phan et al., 2025; Abdirahman et al., 2026). The effects of pesticides occur on different life stages of plant. It may causes sterility, changes in host suitability towards parasites, increase the parastoids population and mortality of plant may cause. This has made a risk for natural enemeis and pollinators (Rumschlag et al., 2019; Pandya et al., 2024). At the point when natural enemies are decreased, considerable outcomes may result for increased pest population which raise the incidence of reappearance and emission of new pests. The reduction in pollinators decreases yield percentage (Ndakidemi et al., 2016).

Plant extracts known as bio-control or green pest controller can be a good option as compared to chemical fertilizer due to their ecofriendly properties, pest management and yield (Rahman et al., 2016). Plant extracts are increasingly prioritized as eco-friendly alternatives because of their natural origin, lower environmental risks, and potential benefits to human health compared with synthetic chemical pesticides (Khursheed et al., 2022; Angaye et al., 2024). Plant extract make the less use of highly toxic and environmental hazard causing chemicals (Adham et al., 2014; Daraban et al., 2023; Aremu et al., 2024). Phyto diseases and pest control are decrease by extracts. Extract of garlic, ginger and mint are used to control root knot nematodes (Stangarlin et al., 2008). The various kinds of plant concentrates are utilized as biocides, for example, neem, garlic, tobacco, kappettiya, syringe, ginger and numerous others are being used to control and deal with the pest or disease of various plants (Agale et al., 2020; Souto et al., 2021; Akama et al., 2023). The application of neem extracts at different concentrations has demonstrated promising effects in reducing pest infestations in rice, betel leaves, and vegetables (Wylie & Merrell, 2022; Tobing et al., 2023). Similarly, extracts derived from garlic bulbs, tobacco, kappettiya leaf residues, lilac flowers, and neem leaves and seeds, as well as neem oil, have been used as botanical pesticides to manage insect pests affecting tea, rice, betel leaves, and various vegetable crops (Rahman et al., 2016; Haseeb et al., 2026).

Marigold flower is the major source of lutein, one of the members of Xanthophylls family of carotenoids (Gupta et al., 2021). Carotenoids are generally obtained from the flower of

marigold in the food industry which is usually present in carrots, red tomatoes and red salmon but lutein extracted from marigold flower show more antioxidant properties than commonly used carotenoids i.e., 3-carotene and lycopene (Barazana et al., 2002; Eldahshan & Singab, 2013; Meléndez-Martínez et al., 2026). Lutein is not only safe, but can potentially help reduce risks of human chronic diseases (Wang et al., 2005). Marigold had been reported to contain 5-(3-buten-1-ynyl) 2, 2-bithienyl and alpha terthienyl (Weidenhamer et al., 2019). Alpha terthienyl is the most effective organic compound in Marigold (Kareem et al., 2025). Roots of marigold contain flavonoids they also have amines, amides, phenols and ketones (Olabiyi, 2008). In marigold, anti-nematode properties are present due to movement of nematodes from the root tissues that trigger the chemical reaction. A short-lived biotoxin oxygen radical, is considered to eliminate the nematodes in the roots (Hamaguchi et al., 2019; Karakas & Bolukbasi, 2019).

Companion planting is a concept in which two plant species are grown together is such a way that both are synergistically important to both plants growth (Saldanha et al., 2019). Companion plants can control insect pests either directly, by discouraging pest establishment, and indirectly by attracting natural enemies that then kill the pest (Parker et al., 2013). Marigold is preferred by growers as it contain many pest repelling chemicals e.g., thiophene (Marotti et al., 2010). Chilli crops are affected by several major pests, including aphids, whiteflies, lepidopteran insects, and plant-parasitic nematodes, which can cause yield losses ranging from 5% to 80%, depending on pest species, infestation severity, and environmental conditions (Hussain & Abid, 2011; Shivalingaswamy et al., 2022). Furthermore, the excessive or indiscriminate application of conventional synthetic pesticides can contribute to environmental pollution, pesticide residues, the development of pest resistance, and adverse effects on beneficial and non-target organisms (Aktar et al., 2009; Muñoz-Bautista et al., 2025; Abdirahman et al., 2026). Considering the commercial importance of chilli as a high-value crop, the present study was designed to evaluate the effects of pre-harvest foliar applications of vegetable extracts and the synergistic role of marigold intercropping on chilli yield and quality.

Materials and Methods

Experimental design

The experiment was conducted during 2018 under greenhouse conditions at the experimental area of the Department of Horticulture, PMAS-Arid Agriculture University Rawalpindi, Pakistan. Nursery seedlings of hybrid chilli (*Capsicum annuum* L.) cv. Osaka and marigold were raised in nursery trays and subsequently transplanted into the greenhouse. The experiment was laid out in a Completely Randomized Design (CRD), comprising four treatments with three replications, resulting in a total of 12 experimental units. Each experimental unit consisted of 16 chilli plants arranged in four rows and four columns (4 × 4 arrangement), with a plant-to-plant distance of 45 cm and a row-to-row distance of 45 cm. Thus, the experiment comprised a total of 192 chilli plants. Four treatments were evaluated: T_0 (chilli without marigold intercropping or vegetable extract application; untreated control), T_1 (chilli with marigold border intercropping), T_2 (chilli receiving foliar application of vegetable extract), and T_3 (chilli with marigold border intercropping combined with foliar application of vegetable extract). In T_1 and T_3, marigold plants were established along the boundaries of the respective chilli experimental units as a border intercropping arrangement. This arrangement was maintained to evaluate the potential of marigold as a companion plant for reducing insect pest infestation in chilli. Treatments were randomly assigned to the experimental units to minimize positional bias within the greenhouse. For data collection, five plants were randomly selected from each experimental unit, resulting in 15 sampled plants per treatment and 60 sampled plants across the entire experiment.

Preparation and application of vegetable extract

The vegetable extract was prepared using five different vegetables, namely cucumber (*Cucumis sativus*), tomato (*Solanum lycopersicum*), chilli (*Capsicum annuum*), bitter gourd (*Momordica charantia*), and bottle gourd (*Lagenaria siceraria*), along with sugar. Fresh vegetables were collected and thoroughly washed with clean water to remove dust and other impurities. The washed vegetables were cut into small pieces and mixed with sugar to facilitate the extraction of plant constituents. The mixture was processed to obtain a vegetable-based liquid extract. Following extraction, the mixture was filtered to separate the liquid extract from the solid vegetable residues. The filtered vegetable extract was diluted with clean water at a ratio of 1:500 (2 mL of extract per litre of water) before foliar application. This dilution was selected with reference to recommendations for fermented plant extracts used in foliar applications (Ebel & Kissmann, 2019). The diluted vegetable extract was applied uniformly to the foliage of chilli plants under treatments T2 and T3 using a hand-operated sprayer. Foliar application commenced 15 days after transplanting (DAT) and was repeated at weekly intervals until fruit formation. The extract was applied uniformly to ensure adequate coverage of the plant foliage. Treatments T_0 (control) and T_1 (chilli intercropped with marigold) did not receive the vegetable extract. The application schedule was selected with reference to previous studies on foliar application of plant extracts in chilli (Weerasingha & Harris, 2022).

Parameters studied

Plant height was measured with the help of measuring tape from soil level to the terminal growing point of the main stem.

The unit selected was cm and average was calculated. The number of leaves of individual plant was counted and average was calculated. The number of damage leaves of individual plant was counted and average was calculated. Stem diameter in cm was measured by using Vernier caliper and average was calculated. The number of flowers per plant was counted and average was calculated. The number of damage flowers per plant was counted and average was calculated. Insect pests associated with chilli plants were identified through visual observations during the experimental period. The observations focused on the occurrence of major insect pests, particularly thrips and aphids, on chilli plants under different treatments. Pest occurrence was assessed visually, and the observed insect types were recorded according to their apparent morphological characteristics. No laboratory-based taxonomic confirmation or species-level identification was performed. Therefore, pest identification in this study was limited to the general insect groups recognizable through field observations. The number of insects present on each plant was counted manually to determine the insect population per plant. The number of fruits per plant was counted and average was calculated. The number of pest damaged fruits per plant was also counted.

Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) to determine the statistical significance of differences among the treatments. The significance of treatment effects was evaluated at the 5% probability level ($p \leq 0.05$). When the ANOVA indicated significant differences among treatment means, the least significant difference (LSD) test was applied for mean comparison at the 5% significance level.

Results

Plant height

The results revealed that the maximum plant height at 75 days after transplanting (DAT) was recorded in T_3 (marigold intercropping combined with vegetable extract application), with a value of 63.45 cm, followed by T_2 (vegetable extract application) with 58.475 cm. In T_1 (marigold intercropping), the maximum plant height was 55.65 cm at 75 DAT, whereas the minimum height of 45.975 cm was recorded in control (T_0) (Fig. 1). Comparison of treatment means revealed significant differences in plant height among the treatments. T_3 produced the highest mean plant height of 44.85 cm followed by T_2 with 42.53 cm. T_1 recorded a mean plant height of 39.44 cm, while the lowest mean height of 34.265 cm was observed in control (T_0). These results indicate that the combined application of marigold intercropping and vegetable extract promoted greater plant growth than either treatment applied individually or the untreated control. Regarding the effect of transplanting time, plant height increased progressively across the different observation periods. The highest overall mean plant height (55.881 cm) was recorded at 75 DAT, followed by 50.8441 cm at 60 DAT. The mean plant height at 45 DAT was higher than those recorded at 15 and 30 DAT, whereas the minimum mean height (21.387 cm) was observed at 15 DAT. At 30 DAT, the mean plant height increased to 43.569 cm, indicating progressive vegetative growth over time.

Number of leaves

Statistical analysis revealed that the maximum number of leaves per plant was recorded in T_3, where marigold was grown as a companion crop with chillies and vegetable extract was applied as a foliar spray. The highest value was 183.57 at 75 days after transplanting (DAT), followed by T_2, which recorded 155.50 leaves per plant at 75 DAT. This was followed by T_3 at 60 DAT, with a value of 144.12 (Fig. 2). The number of leaves per plant exhibited an increasing trend with the advancement of plant growth. The minimum value was recorded in T_0 (control), with 91.30 leaves per plant at 75 DAT. Moreover, T_2 showed a considerable response, recording 133.81 leaves per plant at 75 DAT, although its response was lower than that of the higher-performing treatment. Regarding treatment means, T_3 (marigold intercropping with chillies combined with foliar application of vegetable extract) produced the maximum mean number of leaves per plant (108.69). This was followed by T_2 (foliar application of vegetable extract to chillies), which recorded a mean of 96.84 leaves per plant. T_1 also showed a higher mean number of leaves per plant than the control, with a value of 87.33, whereas the minimum mean value (72.14) was recorded in T_0 (control). Similarly, the mean number of leaves per plant increased significantly with the advancement of time. The maximum mean value was recorded at 75 DAT (141.05 leaves per plant), followed by 60 DAT, with 121.02 leaves per plant. In contrast, the minimum mean number of leaves was observed at 15 DAT (41.41 leaves per plant), which may be attributed to the relatively early growth stage of the plants following transplanting. The number of leaves recorded at 30 and 45 DAT was significantly higher than that at 15 DAT, although the values remained lower than those recorded at later growth stages.

Number of damage leaves

Statistical analysis revealed significant differences among the treatments in terms of the mean number of damaged leaves per plant. The minimum mean number of damaged leaves (3.012) was recorded in T_3, where marigold intercropping was combined with vegetable extract application. This treatment effectively reduced insect infestation and minimized leaf damage, demonstrating better pest management compared with the other treatments (Fig. 3). The second-lowest mean number

of damaged leaves (5.5) was observed in T_2, where vegetable extract was applied alone. T_1 (marigold intercropping) also showed a reduction in leaf damage, with a mean of 6.74 damaged leaves per plant. However, the maximum mean number of damaged leaves (12.38) was recorded in the untreated control (T_0), indicating greater insect damage in the absence of pest management interventions. The combined application of marigold intercropping and vegetable extract (T_3) was more effective in reducing leaf damage than either treatment applied individually. Statistical analysis of damaged leaves across different observation periods revealed a significant increase in leaf damage over time. The minimum mean number of damaged leaves (4.78) was recorded at 30 days after transplanting (DAT). The number of damaged leaves increased progressively with crop age, reaching its maximum value (12.53) at 75 DAT.

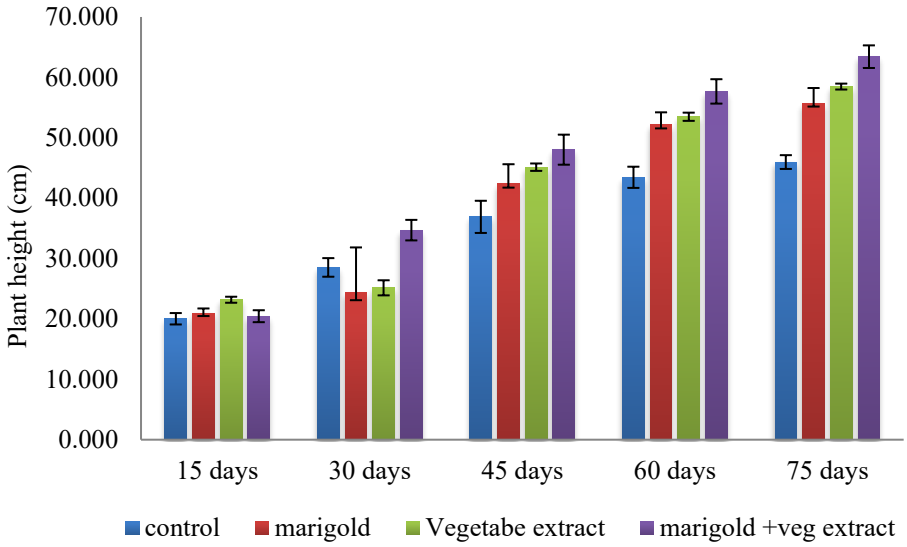


Fig. 1 Effect of marigold as a companion crop and foliar application of vegetable extract on plant height (cm) in chillies at different time interval

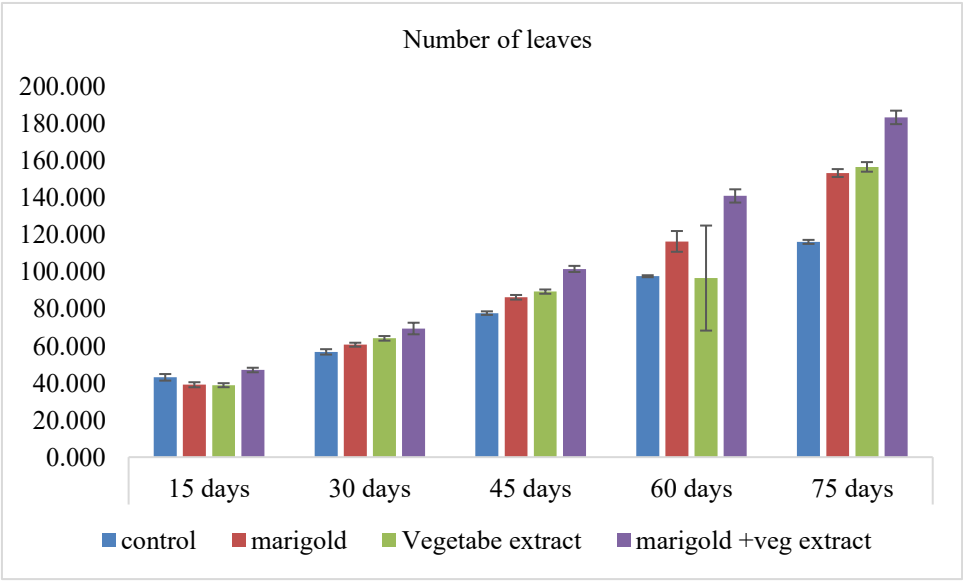


Fig. 2 Effect of marigold as a companion crop and foliar application of vegetable extract on number of leaves in chillies at different time interval

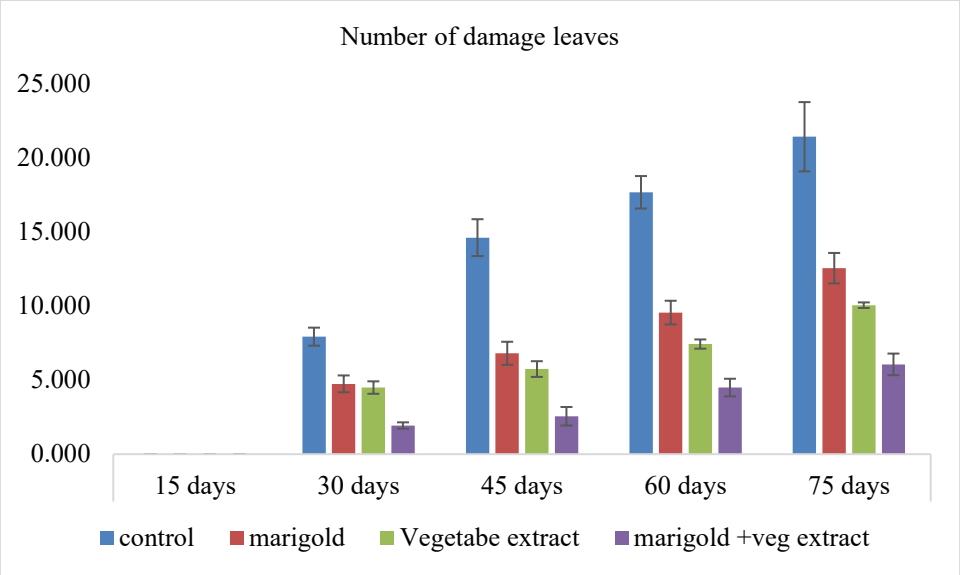


Fig. 3 Effect of marigold as a companion crop and foliar application of vegetable extract on number of damaged leaves in chillies at different time interval

Stem diameter

Statistical analysis of stem diameter revealed non-significant differences among treatments, whereas significant differences were observed among sampling intervals (Table 1). Among the treatments, T_3 (chilli plants intercropped with marigold and treated with foliar application of vegetable extract) exhibited the highest stem diameter at 75 days after transplanting (DAT), with a mean value of 1.74 cm. This was followed by T_2 (chilli plants treated with vegetable extract), which recorded a stem diameter of 1.68 cm, and T_1 (chilli plants intercropped with marigold), with a mean value of 1.65 cm. The lowest stem diameter was recorded in T0 (control), with a mean value of 1.52 cm. Regarding the effect of sampling intervals, the highest mean stem diameter was recorded at 75 DAT (1.74 cm), followed by 60 DAT (1.44 cm), 45 DAT (1.09 cm), 30 DAT (0.69 cm), and 15 DAT (0.46 cm). The minimum stem diameter was observed at 15 DAT, while the maximum was recorded at 75 DAT. The stem diameter increased progressively with plant age across all treatments. These findings indicate that sampling time had a significant effect on stem diameter, whereas the differences among treatments were statistically non-significant. The results also suggest that stem diameter increased consistently with plant growth, irrespective of the treatment applied. Although T_3 recorded the highest numerical value and T0 the lowest, the differences among treatments were statistically non-significant.

Table 1 Effect of marigold as a companion crop and foliar application of vegetable extract on stem diameter (cm) in chillies at different time interval

Treatment	Days	Stem diameter (cm)
	15	0.45 ± 0.009^{i}
	30	0.65 ± 0.026^{h}
T_0	45	1.02 ± 0.051^{fg}
	60	1.29 ± 1.032^{e}
	75	1.52 ± 0.137^{c}
	15	0.46 ± 0.046^{i}
	30	0.66 ± 0.013^{h}
T_1	45	1.00 ± 0.040^{g}
	60	1.34 ± 0.067^{e}
	75	1.65 ± 1.320^{b}
	15	0.46 ± 0.041^{i}
	30	0.67 ± 0.067^{h}
T_2	45	1.02 ± 0.020^{fg}
	60	1.43 ± 0.057^{d}
	75	1.68 ± 0.084^{ab}
	15	0.33 ± 0.264^{j}
	30	0.69 ± 0.062^{h}
T_3	45	1.09 ± 0.109^{f}
	60	1.44 ± 0.029^{cd}
	75	1.74 ± 0.070^{a}

Means followed by a same letter are not significantly different at $p = 0.05$; Values after ± sign indicate standard deviation

Number of flowers

Statistically analyzed data for number of flowers for treatments showed significant results with highest number of flowers 81.25 was recorded in T_3 at 60 days followed by T_2 at 60 days its mean value 76.69 overlapped by T_1 at 60 days having mean value 76.63. Mean of number of flowers show significant difference for treatments with maximum mean of 47.30 of T_3 in which marigold and vegetable extract gave

significant results together shown in Fig. 4. T_3 was followed by T_2 in which vegetable extract was sprayed gave significant result with mean of 40.94. Minimum number of flowers was observed in T_0 control block having value 31.387 flowers per plant. Comparison of number of flowers to days show significant differences its maximum value was notices at 60 days having mean 73.6 followed by mean at 45 days having value 52.78. Other values also show significance but not as much as at 45 and 760 days. Mean umber of flowers at 15, 30 and 75 days are 32.29, 5.30 and 34.00, respectively.

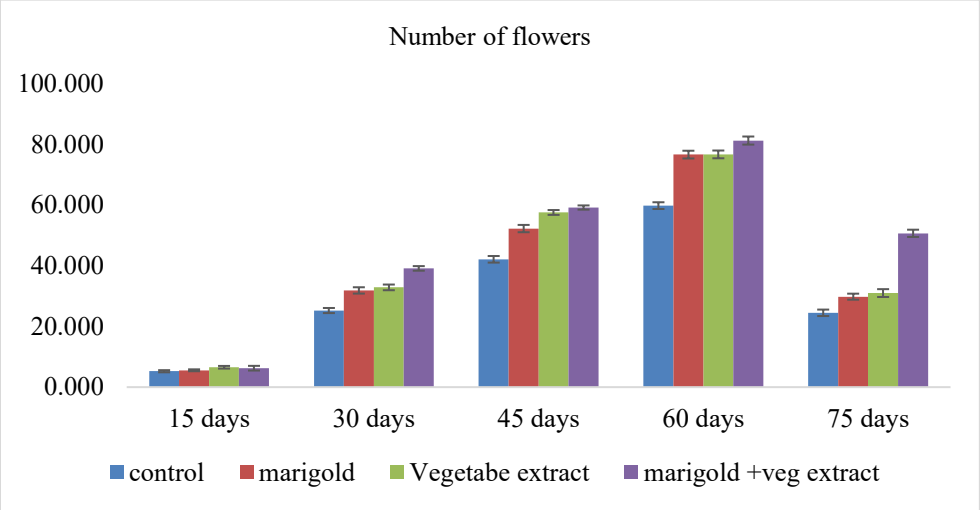


Fig. 4 Effect of marigold as a companion crop and foliar application of vegetable extract on number of flowers in chillies at different time interval

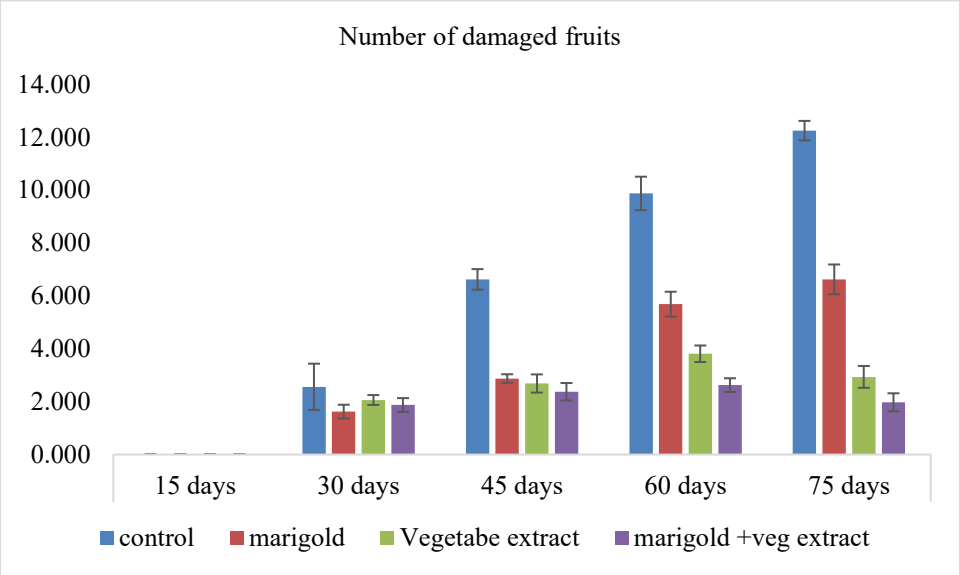


Fig. 5 Effect of marigold as a companion crop and foliar application of vegetable extract on number of damaged fruits in chillies at different time interval

Number of damage flowers

Significant differences were observed among treatments in terms of the number of damaged flowers per plant (Table 2). The highest number of damaged flowers (16.94 per plant) was recorded in T0 at 75 days after transplanting (DAT), followed by T_0 at 60 and 45 DAT, with 13.25 and 9.57 damaged flowers per plant, respectively. These results indicate that the untreated control (T_0) experienced the greatest flower damage throughout the observation period. Treatment T1 ranked next, recording 5.81 damaged flowers per plant at 60 DAT, with an overall mean of 3.64 damaged flowers per plant.

In contrast, T3, which involved marigold intercropping combined with plant-derived extracts, showed comparatively better performance in reducing flower damage. Under T3, the number of damaged flowers was 2.88 per plant at 60 DAT, while the reported overall mean was 1.41 damaged flowers per plant (Table 3). Regarding the effect of sampling time, the mean number of damaged flowers per plant varied significantly among observation periods. The highest mean number of damaged flowers was recorded at 60 days after transplanting (DAT), with 7.10 flowers per plant, followed by 75 DAT (6.30), 45 DAT (5.00), and 30 DAT (3.60). No flower damage was recorded at 15 DAT. The results demonstrate that marigold intercropping combined with foliar application of plant-derived extracts (T_3) was more effective in minimizing flower damage than the other treatments. The progressive increase in flower damage in the untreated control suggests greater pest pressure in the absence of management practices.

Table 2 Effect of marigold as a companion crop and foliar application of vegetable extract on number of damaged flowers in chillies at different time interval

Treatment	Days	Number of damage flowers
	15	0.00 ± 0.000^{k}
	30	7.44 ± 0.298^{d}
T_0	45	9.57 ± 0.479^{c}
	60	13.25 ± 10.600^{b}
	75	16.94 ± 1.525^{a}
	15	0.00 ± 0.000^{k}
	30	4.44 ± 0.444^{f}
T_1	45	3.88 ± 0.078^{fg}
	60	5.81 ± 0.232^{e}
	75	4.06 ± 0.203^{f}
	15	0.00 ± 0.000^{k}
	30	2.13 ± 0.170^{hi}
T_2	45	4.06 ± 0.365^{f}
	60	6.44 ± 0.644^{de}
	75	2.88 ± 0.058^{gh}
	15	0.00 ± 0.000^{k}
	30	0.38 ± 0.304^{jk}
T_3	45	2.50 ± 0.225^{h}
	60	2.88 ± 0.288^{gh}
	75	1.31 ± 0.026^{ij}

Means followed by a same letter are not significantly different at $p = 0.05$; Values after ± sign indicate standard deviation

Type of attacking pest

Visual observations revealed the occurrence of two major insect pest groups, namely thrips and aphids, on chilli plants during the experimental period. The occurrence of these pests varied among treatments and sampling periods. Treatment T_3, which involved the application of marigold and plant extract, showed comparatively lower pest occurrence than that of other treatments. Only a minor occurrence of thrips was visually observed in T3, whereas aphids were not observed during the recorded observations. In contrast, both thrips and aphids were observed in the untreated control (T_0). Treatments T_1 and T_2 also exhibited lower pest occurrence than that of untreated control; however, pest occurrence was comparatively higher than in T_3. These observations indicate differences in the occurrence of visually identified insect pests among the treatments, with T_3 showing the lowest observed pest occurrence. Regarding the temporal pattern, pest occurrence was relatively low at 30 days after transplanting and generally increased during subsequent observations. However, the effect of sampling time was not statistically significant. The field observations suggest that the application of marigold and plant extract was associated with reduced pest occurrence in chilli plants. Because pest identification was based on visual observations, these findings should be interpreted in terms of observed pest occurrence rather than confirmed species-level differences.

Insect population per plant

Statistical analysis revealed significant differences among the treatments in terms of insect population per plant (Table 3). The maximum mean insect population was recorded in the untreated control (T0), where both thrips and aphids were observed. The insect population in T0 reached its highest level at 60 days after transplanting (DAT), with a mean of 6.94 insects per plant. T0 was followed by T1, in which marigold was planted along the borders of the chilli crop. The mean insect population in T1 was 2.63 insects per plant, with the population reaching a maximum of 3.750 insects per plant at 60 DAT. T2 (where vegetable extract was applied as a foliar spray) also demonstrated effectiveness in reducing insect infestation, with a mean insect population of 1.96 insects per plant. The minimum mean insect population (1.23 insects per plant) was recorded in T3, where marigold intercropping was combined with foliar application of vegetable extract. This treatment demonstrated greater effectiveness in suppressing insect populations than either marigold intercropping or vegetable extract application alone. Regarding the effect of observation periods, insect population showed a non-significant difference across the different DAT intervals. The maximum mean insect population (3.92 insects per plant) was recorded at 60 DAT, followed by 3.36 insects per plant at 75 DAT. In contrast, the minimum mean insect population (2.55 insects per plant) was observed at 30 DAT. Although the differences across observation periods were statistically non-significant, the results indicated a numerical increase in insect population from 30 DAT to 60 DAT, followed by a decline at 75 DAT. The results clearly indicated that the combined application of marigold intercropping and vegetable extract (T_3) was the most effective approach for reducing insect populations in chilli. The untreated control (T_0) consistently recorded the highest insect infestation, highlighting the importance of adopting suitable pest management strategies. Although insect populations varied numerically across

observation periods, the differences were statistically non-significant.

Table 3 Effect of marigold as a companion crop and foliar application of vegetable extract on insect population per plant in chillies at different time interval

Treatment	Days	Insect population per plant
	15	0.00 ± 0.000^{h}
	30	3.50 ± 0.140^{bc}
T_0	45	6.00 ± 0.300^{a}
	60	6.68 ± 5.344^{a}
	75	6.94 ± 0.625^{a}
	15	0.00 ± 0.000^{h}
	30	2.69 ± 0.269^{bcde}
T_1	45	3.13 ± 0.063^{bcd}
	60	3.75 ± 0.150^{b}
	75	3.57 ± 0.179^{bc}
	15	0.00 ± 0.000^{h}
	30	2.57 ± 0.206^{cdef}
T_2	45	2.06 ± 0.185^{defg}
	60	3.44 ± 0.344^{bc}
	75	1.75 ± 0.035^{efg}
	15	0.00 ± 0.000^{h}
	30	1.44 ± 0.115^{g}
T_3	45	1.69 ± 0.169^{efg}
	60	1.56 ± 0.031^{fg}
	75	1.44 ± 0.130^{g}

Means followed by a same letter are not significantly different at $p = 0.05$; Values after ± sign indicate standard deviation

Number of fruits

Statistically analyzed data shown in Table 4 depicted that significant results with maximum number of fruits was recorded from T_3 at 65 days after transplanting with value 64.69 followed by T_2 and T_1 at 75 days of transplanting having values 58.56 and 54, respectively. The mean number of fruits differed significantly among treatments, with the highest number recorded in T_3 (64.69 fruits per plant), followed by T_2 (58.56 fruits per plant). The minimum number of fruits was recorded on T_0 with the mean value of 3.00 fruits per plant. Moreover, T_1 also show significant result as compared to T_0 but least value than T_2 and T_3. Comparison between mean number of fruit and number of days also show significant difference.

Number of damage fruits

Results presented significance differences for the number of damaged fruits per plant in all the treatments (Fig. 5). The maximum number of damaged fruits was recorded in T_0 after 75 days of transplanting with value of 12.250 which was followed by T_0 value at 60 and 45 days with values 9.88 and 6.63 respectively. T_0 was followed by T_1 at 75 days after transplanting its value was 6.63 damaged fruits per plant, T_1 mean number of damaged fruits was 3.37. The most significance results were found for T_3 in which marigold and vegetable extract were applied maximum value for damage fruits was after 60 days of transplanting and its value was 2.63, Mean fruit damage value for T_3 was 1.77. Whereas T_2 also show significant results but overall mean was not significant as of T_3, its mean value was 2.30. Number of damaged fruit when compare with time all means shows significant differences in which maximum fruit are damaged after 75 days of transplanting and their means was 5.95 followed by mean after 60 days having value 5.50. Mean after 15, 30 and 45 days also shows significance differences with values 0.00, 2.03 and 2.64, respectively.

Table 4 Effect of marigold as a companion crop and foliar application of vegetable extract on number of fruits in chillies at different time interval

Treatment	Days	Number of fruits
	15	3.00 ± 0.060^{l}
	30	8.38 ± 0.335^{k}
T_0	45	15.94 ± 0.797^{j}
	60	26.00 ± 20.800^{h}
	75	39.25 ± 3.533^{e}
	15	3.31 ± 0.331^{l}
	30	8.50 ± 0.170^{k}
T_1	45	23.00 ± 0.920^{i}
	60	39.56 ± 1.978^{e}
	75	54.00 ± 43.200^{c}
	15	3.06 ± 0.275^{l}
	30	10.94 ± 1.094^{k}
T_2	45	29.06 ± 0.581^{g}
	60	44.81 ± 1.792^{d}
	75	58.56 ± 2.928^{b}
	15	2.31 ± 0.023^{l}
	30	9.50 ± 0.760^{k}
T_3	45	32.94 ± 2.965^{f}
	60	51.88 ± 5.188^{c}
	75	64.69 ± 1.294^{a}

Means followed by a same letter are not significantly different at $p = 0.05$; Values after ± sign indicate standard deviation

Discussion

In the present study, plant height was one of the growth parameters used to evaluate the effectiveness of marigold intercropping and plant-derived sprays in chilli (*Capsicum annuum* L.). The observed improvement in plant height under the more effective treatments suggests that these eco-friendly management practices may have contributed to more favourable growing conditions. Reducing insect infestation helps preserve photosynthetically active leaf area and minimizes the diversion of plant resources towards repairing damaged tissues. Consequently, plants may retain greater capacity for vegetative growth. However, the extent to which pest suppression contributed to increased height cannot be separated from any direct effects of the sprays or other treatment-related differences without additional physiological

measurements. The results can be interpreted in the context of botanical pest management, as plant-derived products contain diverse compounds that may interfere with insect feeding, movement, development, or survival. Tavares et al. (2021) reviewed evidence for the insecticidal potential of aqueous and ethanolic plant extracts, including extracts from *Azadirachta indica*, *Capsicum annuum*, *Nicotiana tabacum*, and *Tagetes erecta*. Their review supports the potential of botanical products as pest-management tools, although their effectiveness varies with the plant species, extraction procedure, formulation, target insect, and application conditions (Tavares et al., 2021). Thus, the increased plant height observed in the present study may be associated with the effectiveness of plant-derived extracts in suppressing insect pests, including aphids, which feed on plant sap and can impair crop growth. Botanical extracts have demonstrated potential as environmentally friendly pest management agents, helping to reduce pest populations and minimize crop damage (Tavares et al., 2021). Recent research has also demonstrated the efficacy of plant-based insecticidal formulations against aphids, highlighting their potential for sustainable crop protection (Ngegba et al., 2022). Similarly, Wood et al. (1996) reported maximum plant height when different extracts were applied. It was possibly due to the insecticidal properties of extracts by reducing the insects, aphids from sucking on the crops.

The number of leaves is an important indicator of vegetative development because leaves provide the principal surface for photosynthesis and contribute to the production of assimilates required for flowering and fruit development (Olanlokun et al., 2026). In the present study, differences in leaf number among treatments suggest that the tested management practices influenced the development or retention of foliage. Where plant-derived sprays and marigold intercropping produced more leaves than the untreated or sole-crop treatment, the response may reflect improved plant vigour and reduced injury from herbivorous insects. Effective pest management preserves young leaves and growing points that might otherwise be damaged by sap-feeding or chewing insects. Aphids, for example, remove phloem sap and may contribute to leaf curling, distortion, and reduced plant vigour when infestations are sufficiently severe (Gonzales Diaz et al., 2026). However, greater leaf number does not necessarily demonstrate direct stimulation by a plant extract; it may also result from lower pest pressure, differences in plant development, or treatment-related changes in growing conditions. Similar to our findings, Hanafy et al. (2012) reported favourable plant growth following applications of garlic, yeast, aloe, and henna extracts.

Stem diameter is an important morphological trait because it is associated with structural support and the capacity of a plant to maintain its canopy and developing fruits (Liu et al., 2026). In the present study, variation in stem diameter among treatments indicates that the management practices may have influenced chilli plant development. If the combined marigold-intercropping and plant-derived-spray treatment produced the greatest stem diameter, this would suggest that integrating the two practices may have provided a more favourable overall growing environment than relying on a single practice. It may be due to the reason that the reduced insect pressure helps plants maintain healthy foliage and sustain carbon assimilation, supporting the growth of stems and other organs. Some plant-derived preparations may also supply nutrients or contain biologically active compounds, but these effects depend on their composition and preparation. Foidl et al. (2001) reported that the application of *Moringa oleifera* leaf extract can enhance crop yield by approximately 20–35%. Foliar application of the extract has been associated with improved vegetative growth, including greater root development and increased leaf density. Furthermore, it may promote fruit formation, increase fruit size, and ultimately improve overall crop yield. Park et al. (2026) investigated the effects of different French marigold (*Tagetes patula* L.) companion-cropping ratios on substrate properties and the growth performance of hot pepper (*Capsicum annuum* L.) under urban rooftop agricultural conditions. Their findings revealed that a pepper-to-marigold ratio of 2:1 resulted in significantly greater leaf length and width, a higher number of fruits, and increased shoot dry weight compared with pepper monoculture. Moreover, companion cropping was associated with improved substrate moisture regulation and lower pest-feeding incidence, although the differences in pest damage were not statistically significant. These findings support the potential of marigold intercropping as an environmentally friendly approach to improving crop growth and productivity. The results are relevant to the present study, in which marigold intercropping and botanical foliar sprays were evaluated as sustainable strategies for enhancing chilli growth and reducing pest damage. However, Park et al. (2026) examined companion cropping rather than foliar botanical applications, highlighting the need to investigate the combined effects of these approaches for more effective and sustainable pest management.

Leaf damage is a direct indicator of the pressure exerted by herbivorous insects and can provide useful evidence of the effectiveness of crop-protection treatments (Soujanya et al., 2022). In the present study, the reported differences in damaged leaves suggest that pest injury varied among the experimental treatments. A lower number of damaged leaves in plots receiving marigold intercropping and plant-derived sprays would indicate that these practices helped protect the chilli canopy. Marigold (Tagetes spp.) is used in diversified cropping systems because its presence may affect pest movement, host-plant recognition, and the distribution of insects within the crop. Its influence may arise from the physical presence of companion vegetation, differences in plant odours, and changes in the availability of resources for natural enemies (Awasthi, 2025). These processes can reduce the likelihood that certain herbivores will locate or remain on

the principal crop. However, their effects are not uniform across pest species, companion-plant combinations, or environmental conditions. Our findings are consistent with the previous research study conducted by Parihar et al. (2025) who described marigold as a potential trap or companion crop in solanaceous vegetable production, including chilli, tomato, eggplant, and potato. However, the effectiveness of marigold depends on the target pest and cropping arrangement; the plant should not be assumed to control every insect in the same way. Yousefi et al. (2024) found that intercropping significantly reduced herbivore abundance overall and increased predator abundance, although responses varied with crop species, intercrop arrangement, and the ecological characteristics of the arthropods.

In our research study, the number of aphids was higher in the sole pepper plot than in the intercropped pepper this was similar to the results of the (Degri & Samaila, 2014) who reported that fruit borer larva was found minimum when tomato was intercropped and maximum in sole crop tomato. The mechanism responsible for this reduction of aphids number on pepper intercrop was due to unsuitable hosts acting as trap plants and barrier resulting to their starvation. Similarly (Degri & Yoriyo, 2010) reported that adults and nymphs of aphid and whitefly were reduced by application of 2 extracts. This was similar to the results of an earlier study that reported pepper intercropped with non-host crops lowered aphid infestation and damage resulting to higher fruit yield than that of monocrop (Hussien & Samad, 1993). The observed differences in insect pest occurrence among treatments suggest that companion planting and the application of plant extracts may contribute to reducing pest occurrence in chilli cultivation. Similar findings were reported by Nadaf (2002), who observed that growing chilli and Tagetes spp. as companion crops at an 18:1 ratio resulted in reduced populations of *Helicoverpa armigera* larvae and minimized fruit damage in chilli. These findings support the potential role of marigold as a companion plant in integrated pest management. In the present study, T3, which involved marigold and plant extract application, exhibited comparatively lower occurrence of visually identified insect pests than the other treatments. This pattern suggests that the combined treatment may have influenced pest occurrence in chilli plants. However, the specific mechanisms responsible for this observed response, such as pest repellence, altered host-plant attractiveness, or the activity of natural enemies, were not directly investigated. Furthermore, insect identification was based on visual field observations rather than taxonomic confirmation. Therefore, further investigations involving detailed insect identification and quantitative pest population monitoring are required to establish the mechanisms underlying the observed treatment effects. Intercropping can influence pest distribution through several ecological processes. Companion plants may interfere with the visual and chemical cues that insects use to locate their host plants, disrupt the continuity of the main crop, and thereby reduce the likelihood of insects encountering suitable host plants (Finch & Collier, 2012; Parker et al., 2013).

Gunaeni et al. (2024) evaluated chilli intercropped with coriander, celery, and bunching onion in field experiments conducted in Indonesia. Their study reported reduced damage from several major chilli pests under intercropping, with coriander-associated intercropping showing particularly favourable results for thrips, *Helicoverpa armigera*, and *Bactrocera dorsalis*. The number of insects per plant provides a more direct measure of pest pressure than visual damage alone. In the present study, the reported differences in insect population among treatments suggest that the cropping system and botanical applications influenced the abundance of pests on chilli plants. Where pest numbers were lower in intercropped or sprayed treatments than in sole-cropped controls, the results indicate that these practices may have contributed to suppressing insect colonization or persistence. A similar study was conducted by Wenda-Piesik and Piesik (2020) who reported that pest populations are frequently higher and expand more rapidly in homogeneous monocropping environments due to a continuous food supply and a lack of natural predators. Furthermore, modern agroecological assessments by Khilare et al. (2022); Kaur et al. (2024) demonstrated that this elevated pest vulnerability in simplified monocultures directly translates to greater crop damage and significant financial or yield losses, whereas diversified cropping systems disrupt pest life cycles, foster natural biological controls, and secure higher total productivity.

Fruit number is a key production parameter because it reflects the plant's ability to develop and retain reproductive structures through flowering and fruit set (Bu et al., 2025). In the present study, differences in fruit number among treatments suggest that the pest-management practices may have influenced reproductive performance. If the plots receiving combined marigold intercropping and plant-derived sprays produced more fruits, because the reduced pest injury helped plants maintain functional foliage and reproductive structures during fruit development. Pest management may affect fruit production indirectly by limiting damage to leaves, flowers, and developing fruits. When the plant retains a healthy canopy, it may sustain photosynthesis and provide assimilates for fruit growth (Yogesh et al., 2025). Our findings are consistent with those of Baloch et al. (2026), who reported that the integration of botanical applications with diversified planting systems can improve nutrient uptake and contribute to pest suppression in solanaceous crops. These findings support the potential of combining botanical pest management with intercropping to promote crop performance and sustainable pest control. However, differences in growth habits, nutrient requirements, and competitive responses between tomato and chilli should be considered when interpreting these results. Similar findings were reported by Quaggio et al. (2002), who highlighted the importance of potassium in improving fruit set, strengthening plant stems, and enhancing resistance to certain diseases.

Plant-derived extracts may also contribute to potassium supply, depending on their composition and concentration. According to Gupta (2003), potassium plays a vital role in activating numerous enzymes involved in essential biochemical reactions, thereby supporting plant growth, metabolism, and overall physiological functioning. These findings suggest that the potassium content of botanical extracts may contribute to improved crop performance and fruit development. However, the extent of these effects depends on the potassium concentration of the extract and its availability to the plant.

Conclusion

In this study, combined application of marigold intercropping and foliar vegetable extract (T3) generally produced the most favourable results for chilli growth, yield-related traits, and insect pest management under greenhouse conditions. Compared with the untreated control, T3 recorded the highest plant height, number of leaves, flowers, and fruits per plant, along with lower numbers of damaged leaves, flowers, and fruits and a reduced insect population. The individual application of marigold (T1) and vegetable extract (T2) also improved several growth and yield-related parameters compared with the control. Although T3 generally showed better numerical performance than the individual treatments, the differences among treatments were not statistically significant for all measured parameters, including stem diameter. The findings highlight the potential value of combining companion planting with botanical foliar applications as an integrated approach to chilli cultivation and pest management. The novelty of this study lies in evaluating the combined and individual effects of marigold intercropping and vegetable extract application within the same experimental framework. Further studies under field conditions are recommended to validate these findings and investigate the underlying mechanisms and economic feasibility of this integrated approach.

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Declarations

i. Ethics approval and consent to participate: This study did not involve human participants, human data, or animal studies; therefore, ethical approval was not required.

ii. Competing interests: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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References

Abdirahman, A. A., Demirözer, O., Hassan, A. S., & Jisow, A. M. (2026). Impact of synthetic agricultural pesticides on non-target insects. *Cross Current International Journal of Agriculture and Veterinary Sciences, 8*(1), 12–22. https://doi.org/10.36344/ccijavs.2026.v08i01.002

Adham, S. A., Al Harrasi, I., Al Haddabi, I., Al Rashdi, A., Al Sinawi, S., Al Maniri, A., & Coomber, B. L. (2014). Immunohistological insight into the correlation between neuropilin-1 and epithelial-mesenchymal transition markers in Epithelial ovarian cancer. *Journal of Histochemistry & Cytochemistry, 62*(9), 619-631.

Agale, S., Wankhede, S. Y., Ingle, N., & Kamthe, H. (2020). Botanicals methods of plant disease control. In *Current research and innovations in plant pathology* (Chapter 3, pp. 1–188). AkiNik Publications.

Ahmad, M. F., Ahmad, F. A., Alsayegh, A. A., Zeyaullah, M., AlShahrani, A. M., Muzammil, K., Saati, A. A., Wahab, S., Elbendary, E. Y., Kambal, N., Abdelrahman, M. H., & Hussain, S. (2024). Pesticides impacts on human health and the environment with their mechanisms of action and possible countermeasures. *Heliyon, 10*(7), e29128. https://doi.org/10.1016/j.heliyon.2024.e29128

Akama, C. K., Amiteye, S., Appiah, A. S., Kpentey, P. B., Appiah, R., Kutufam, J. T., Dzimega, D. A., & Amenorpe, G. (2023). Assessment of different rates of neem extracts as bio-pesticide for the control of insect vectors and associated viral diseases in okra. *African Journal of Agricultural Research, 19*(4), 364-373. https://doi.org/10.5897/AJAR2022.16192

Akhter, M. J., Akhter, S., Islam, S., Sarker, M. S. H., & Hasan, S. M. K. (2024). Varietal influence on bioactive compounds and antioxidant activity in chilies during development stages. *Heliyon, 10*(17), e37406. https://doi.org/10.1016/j.heliyon.2024.e37406

Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology, 2*(1), 1–12. https://doi.org/10.2478/v10102-009-0001-7

Ali, I. M. (2023). The harmful effects of pesticides on the environment and human health: A review. *Diyala Agricultural Sciences Journal, 15*(1), 114–126. https://doi.org/10.52951/dasj.23150112

Ali, M. M., Khalid, N. I., Wondi, M. H., Haris, N. I. N., & Azman, P. N. M. A. (2025). Exploring the nutritional values, volatile compounds, health benefits, and potential food products of chilli (*Capsicum annuum*): A comprehensive review. *Food Chemistry, 490*, 145091. https://doi.org/10.1016/j.foodchem.2025.145091

Amekawa, Y., Hongsibsong, S., Sawarng, N., & Gebre, G. G. (2023). Chili pepper farmers' pesticide use and residues under Thailand's Public Good Agricultural Practices Standard: A case study in Chiang Mai Province. *Agriculture, 13*(5), 1105. https://doi.org/10.3390/agriculture13051105

Amin, M., Ali, A., Anser, M., Shahid, R., Javed, T., Javaad, H. W., & Pervez, M. (2025). Yield performance and quality assessment of hot pepper genotypes under field conditions in Pakistan. *Insights-Journal of Life and Social Sciences, 3*(5), 151–159.

Angaye, T. C. N., Ukoroije, R. B., & Angaye, G. P. (2024). Plant-derived pesticides (PDPs) versus synthetic pesticides: An eco-friendly approach to biodiversity conservation. *International Journal of Innovative Environmental Studies Research, 12*(1), 67–75.

Aremu, A. O., Omogbene, T. O., Fadiji, T., Lawal, I. O., Opara, U. L., & Fawole, O. A. (2024). Plants as an alternative to the use of chemicals for crop protection against biotic threats: Trends and future perspectives. *European Journal of Plant Pathology, 170*(4), 711–766. https://doi.org/10.1007/s10658-024-02924-y

Awasthi, P. (2025). Marigolds as a companion crop: Impact on pest control and pollinator attraction in mixed cropping systems. *Sustainability Science and Resources, 9*(3), 39–52. https://doi.org/10.55168/ssr2809-6029.2025.9003

Bal, S., Sharangi, A. B., Upadhyay, T. K., Khan, F., Pandey, P., Siddiqui, S., ... Yadav, D. K. (2022). Biomedical and antioxidant potentialities in chilli: Perspectives and way forward. *Molecules, 27*(19), 6380. https://doi.org/10.3390/molecules27196380

Baloch, A. W., Khan, M. S., & Ahmed, N. (2026). Integrated botanical applications and diversified planting systems in solanaceous crops: Impacts on nutrient uptake and pest suppression. *International Journal of Vegetable Science, 32*(1), 45–58.

Barzana, E., Rubio, D., Santamaria, R. I., Garcia-Correa, O., Garcia, F., Ridaura Sanz, V. E., & López-Munguía, A. (2002). Enzyme-mediated solvent extraction of carotenoids from marigold flower (*Tagetes erecta*). *Journal of Agricultural and Food Chemistry, 50*(16), 4491-4496.

Bhattacharya, A., Chattopadhyay, A., Mazumdar, D., Chakravarty, A., & Pal, S. (2010). Antioxidant constituents and enzyme activities in chilli peppers. *International Journal of Vegetable Science, 16*(3), 201-211.

Biswas, S. K., Rahman, S., Kobir, S. M. A., Ferdous, T., & Banu, N. A. (2014). A review on impact of agrochemicals on human health and environment: Bangladesh perspective. *Plant Environment Development, 3*(2), 31-35.

Bu, H., Sun, X., Hu, Y., Gu, G., Yang, Y., & Yu, W. (2025). Research advances in the regulation of fruit size: An integrated perspective of genetic, hormonal, epigenetic, and environmental control. *Biology, 14*(12), 1643. https://doi.org/10.3390/biology14121643

Chili cultivation, production goes up in Pakistan in 2025–26. (2025, November 3). *THE NATION*. Retrieved from https://www.nation.com.pk/03-Nov-2025/chili-cultivation-production-goes-pakistan-2025-26

Daraban, G. M., Hlihor, R.-M., & Suteu, D. (2023). Pesticides vs. biopesticides: From pest management to toxicity and impacts on the environment and human health. *Toxics, 11*(12), 983. https://doi.org/10.3390/toxics11120983

Degri, M. M., & Samaila, A. E. (2014). Impact of intercropping tomato and maize on the infestation of tomato fruit borer *Helicoverpa armigera* (Hubner). *Journal of Agricultural and Crop Research, Londrina, 2*(8), 160-164.

Degri, M. M., & Yoriyo, K. P. (2010). Efficacy of three plant extracts for the control of aphids (Aphis gossypii Glov) (Homoptera; Aphididae) on sweet peppers (*Capsicum annum* L.) (Solanaceae) in Nigeria Sudan Savanna. *International Journal of Food and Agricultural Research, 7*(1), 256-262.

Dias, G. B., Gomes, V. M., Pereira, U. Z., Ribeiro, S. F. F., Carvalho, A. O., Rodrigues, R., & Da Cunha, M. (2013). Isolation, characterization and antifungal activity of proteinase inhibitors from *Capsicum chinese* Jacq. seeds. *Protein Journal, 32*(1), 15-26.

Djian-Caporalino, C., Lefebvre, V., Sage-Daubeze, A. M., & Palloix, A. (2006). Capsicum. *Genetic Resources, Chromosome Engineering, and Crop Improvement. 3*, 186-245.

Ďúranová, H., Valková, V., & Gabriny, L. (2022). Chili peppers (Capsicum spp.): The spice not only for cuisine purposes: An update on current knowledge. *Phytochemistry Reviews, 21*, 1379–1413. https://doi.org/10.1007/s11101-021-09789-7

Ebel, R., & Kissmann, S. (2019). Fermented leaf fertilizers—Principles and preparation. *Organic Farming, 5*(1), 14–22. https://doi.org/10.12924/of2019.05010014

Eldahshan, O. A., & Singab, A. N. B. (2013). Carotenoids. *Journal of Pharmacognosy and Phytochemistry, 2*(1), 225–234.

FAOSTAT., (2017). Food and Agriculture Organization of the United Nations. Production Data. http://www.fao.org/faostat/en/#data/QC

Finch, S., & Collier, R. (2012). The influence of host and non-host companion plants on the behaviour of pest insects in field crops. *Entomologia Experimentalis et Applicata, 142*(2), 87–96. https://doi.org/10.1111/j.1570-7458.2011.01191.x

Foidl, N., Makkar, H. P. S., & Becker, K. (2001, October 20–November 2). What development potential for Moringa products? In *The potential of Moringa oleifera for agricultural and industrial uses*. Conference paper presented in Dar es Salaam, Tanzania.

Gonzales Diaz, A. A., Wang, F., & Feng, H. (2026). Aphid management in crop systems: Current strategies and future perspectives. *Agriculture, 16*(9), 924. https://doi.org/10.3390/agriculture16090924

Gunaeni, N., Setiawati, W., Muharam, A., Karjadi, A. K., Murtiningsih, R., Moekasan, T. K., ... Udiarto, B. K. (2024). Intercropping insect repellent plants (IRPs): A promising strategy for sustainable pest management. *Agronomy Research, 22*, 1434–1445. https://doi.org/10.15159/AR.24.093

Gupta, P. K. (2003). Handbook of Soil, Fertilizer and Manure. Agrobios (India).

Gupta, Y. C., Panwar, S., Banyal, N., Thakur, N., & Dhiman, M. R. (2021). Marigold. In S. K. Datta & Y. C. Gupta (Eds.), *Floriculture and ornamental plants. Handbooks of Crop Diversity: Conservation and Use of Plant Genetic Resources*. Springer, Singapore. https://doi.org/10.1007/978-981-15-1554-5_1-1

Hamaguchi, T., Sato, K., Vicente, C. S. L., & Hasegawa, K. (2019). Nematicidal actions of the marigold exudate α-terthienyl: Oxidative stress-inducing compound penetrates nematode hypodermis. *Biology Open, 8*(4), bio038646. https://doi.org/10.1242/bio.038646

Hanafy, M. S., Saadawy, F. M., Milad, S. M. N., & Ali, A. S. (2012). Effect of some natural extracts on growth and chemical constituents of *Schefflera arboricola*, L. plants. *Journal of Horticultural Science & Ornamental Plants, 4*(1), 26-33.

Haseeb, H., Qamar, S., Siddique, A. B., Khan, A., Shah, H. A., Khan, S. A., Gul, M. H., Farid, J., Rehman, S., & Ahmad, A. (2026). Botanical insecticide against insect pests of tobacco crop at District Swabi. *Physical Education, Health and Social Sciences, 4*(1), 392–397. https://doi.org/10.63163/jpehss.v4i1.1097

Hazara, P., Chattopadhyay, A., Karmakar, K., & Dutta, S. (2011). Modern Technology in Vegetable Production (pp. 236-239)

Hossain, A. S. M. A., Islam, S. M. A., Akhtera, K., Akheter, N., & Muqit, A. (2010). Effect of plant extracts, insecticides and cultural practices on growth characters and disease severity of mungbean yellow mosaic virus. *International Journal of Sustainable Crop Production, 5*(2), 16-20.

Hussain, F., & Abid, M. (2011). Pests and diseases of chilli crop in Pakistan: A review. *International Journal of Biology and Biotechnology, 8*(2), 325–332.

Hussein, M. Y., & Samad, N. A. (1993). Intercropping chilli with maize or brinjal to suppress populations of *Aphis gossypii* Glov., and transmission of chilli viruses. *International Journal of Pest Management, 39*(2), 216-222.

Karakas, M., & Bolukbasi, E. (2019). A review: Using marigolds (Tagetes spp.) as an alternative to chemical nematicides for nematode management. *International Journal of Advanced Engineering, Management and Science, 5*(9), 556–560. https://doi.org/10.22161/ijaems.59.3

Kareem A. H., Kavitha, P. G., Devrajan, K., Venkatesa Palanichamy, N., Raja, K., Thangamani, C., & Sakthivel, V. (2025). Alpha-terthienyl (a novel marigold derivative): An overview on nematicidal potential. *Plant Science Today, 12*(3), 1–13. https://doi.org/10.14719/pst.8256

Kaur, G., Singh, J., & Sharma, R. (2024). Monoculture of crops: A challenge in attaining food security. In A. K. Singh & P. Kumar (Eds.), *Sustainable Agriculture and Food Security Protocols* (pp. 89–112). Cham, Switzerland: Springer.

Khan, A., Shaukat, S.S. & Ahmed, I. (2000). Nematode communities associated with chillies in lower Sindh, Pakistan. *Pakistan Journal of Biological Sciences, 3*, 457-458

Khilare, S., Pawar, R., & Jagtap, S. (2022). Integrated pest management in diverse cropping systems. In S. Kumar & M. K. Meena (Eds.), *Agroecological Approaches for Sustainable Crop Production* (pp. 145–168). Boca Raton, FL: CRC Press.

Khursheed, A., Rather, M. A., Jain, V., Wani, A. R., Rasool, S., Nazir, R., Malik, N. A., & Majid, S. A. (2022). Plant based natural products as potential ecofriendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations and regulatory aspects. *Microbial Pathogenesis, 173*, 105854. https://doi.org/10.1016/j.micpath.2022.105854

Liu, L., Zhan, J., Luo, J., Luo, C., Chen, J., Zhao, G., Wang, Y., Wu, H., & Huang, S. (2026). Cytological and transcriptomic profiling reveals the developmental basis of stem diameter variation in Luffa. *Agronomy, 16*(17), 1740. https://doi.org/10.3390/agronomy16171740

López Castilla, L. del C., Garruña Hernández, R., de la Cruz Castillo Aguilar, C., Martínez-Hernández, A., Ortiz-García, M. M., & Andueza-Noh, R. H. (2019). Structure and genetic diversity of nine important landraces of Capsicum species cultivated in the Yucatan Peninsula,

Mexico. *Agronomy, 9*(7), 376. https://doi.org/10.3390/agronomy9070376

Marin, A., Ferreres, F., Tomás-Barberán, F. A., & Gil, M. I. (2004). Characterization and quantitation of antioxidant constituents of sweet pepper (*Capsicum annuum* L.). *Journal of Agricultural and Food Chemistry, 52*(12), 3861-3869.

Medina-Lara, F., Echevarría-Machado, I., Pacheco-Arjona, R., Ruiz-Lau, N., Guzman-Antonio, A., & Martinez-Estevez, M. (2008). Influence of nitrogen and potassium fertilization on fruiting and capsaicin content in habanero pepper (*Capsicum chinese* Jacq.). *Horticulture Science, 43*(5), 1549-1554.

Meléndez-Martínez, A. J., Morón-Ortiz, Á., Esquivel, P., & Rodriguez-Amaya, D. (2026). Carotenoids. In *Bioactive components for functional foods* (Chapter 5, pp. 91–132). Elsevier. https://doi.org/10.1016/B978-0-443-29983-4.00009-0

Mi, L. T. D., & Giao, N. T. (2022). The use and potential impacts of pesticides in chili farming in the Thanh Binh District, Dong Thap Province, Vietnam. *Journal of Ecological Engineering, 23*(8), 1–11. https://doi.org/10.12911/22998993/150650

Muñoz-Bautista, J. M., Bernal-Mercado, A. T., Martínez-Cruz, O., Burgos-Hernández, A., López-Zavala, A. A., Ruiz-Cruz, S., Ornelas-Paz, J. de J., Borboa-Flores, J., Ramos-Enríquez, J. R., & Del-Toro-Sánchez, C. L. (2025). Environmental and health impacts of pesticides and nanotechnology as an alternative in agriculture. *Agronomy, 15*(8), 1878. https://doi.org/10.3390/agronomy15081878

Nadaf, A. M. (2002). Testing of IPM modules for the management of *Helicoverpa armigera* Hubner in chilli. M Sc. (Agri.) Thesis, University of Agriculture Science, Dharwad, India

Naik, S. R., Gamare, D., & Bhopatrao, A. (2024). Chemical health hazards and toxicity of environmental pollutants on humans, animals and others: An overview. *Journal of Toxicological Studies, 2*(1), 1135. https://doi.org/10.59400/jts.v2i1.1135

Navarro, J. M., Garrido, C., Carvajal, M., & Martinez, V. (2002). Yield and fruit quality of pepper plants under sulphate and chloride salinity. *The Journal of Horticultural Science and Biotechnology, 77*(1), 52-57.

Ndakidemi, B., Mtei, K., & Ndakidemi, P. A. (2016). Impacts of synthetic and botanical pesticides on beneficial insects. *Agricultural Sciences, 7*(6), 364-372. https://doi.org/10.4236/as.2016.76038

Ngegba, P. M., Cui, G., Khalid, M. Z., & Zhong, G. (2022). Use of botanical pesticides in agriculture as an alternative to synthetic pesticides. *Agriculture, 12*(5), 600. https://doi.org/10.3390/agriculture12050600

Olabiyi, T. (2008). Pathogenicity study and nematoxic properties of some plant extracts on the root-knot nematode pest of tomato, *Lycopersicum esculentum* L. Mill. *Plant Pathology Journal 7*(1), 45-49.

Olanlokun, F. S., Dada, O. A., & Ncama, K. (2026). The role of leaf morphology and sustainable management practices on optimizing nitrogen use efficiency of upland rice: A review. *Crops, 6*(2), 46. https://doi.org/10.3390/crops6020046

Pandya, R. P., Patel, H. J., & Kanani, A. N. (2024, November). The impact of pesticides on parasitoids: Challenges and solutions. *The Agriculture Magazine, 4*(3), 230–234.

Paredes Andrade, N. J., Monteros-Altamirano, A., Tapia Bastidas, C. G., & Sørensen, M. (2020). Morphological, sensorial and chemical characterization of chilli peppers (Capsicum spp.) from the CATIE genebank. *Agronomy, 10*(11), 1732. https://doi.org/10.3390/agronomy10111732

Parihar, M., Dhar, S., & Sahu, P. (2025). Marigold as a trap crop: Efficacy and mechanism for sustainable pest and nematode management in solanaceous vegetable crops: A review. *Journal of Ornamental Horticulture, 28*(1), 20–28. https://doi.org/10.59582249-880X.2025.00005.3

Park, J.-H., Park, S.-H., Park, J.-M., Chae, Y.-J., Yoon, Y.-H., & Ju, J.-H. (2026). Effects of companion cropping ratios of French marigold on substrate properties and vegetative growth of hot pepper in urban rooftop agriculture. *Horticulturae, 12*(10), 1216. https://doi.org/10.3390/horticulturae12101216

Parker, J. E., Snyder, W. E., Hamilton, G. C., & Rodriguez-Saona, C. (2013). Companion planting and insect pest control. In S. Soloneski & M. L. Larramendy (Eds.), *Weed and pest control: Conventional and new challenges*. IntechOpen. https://doi.org/10.5772/55044

Perez Castaneda, L. M., Castanon Najera, G., & Mayek Perez, N. (2008). Diversidad morfologica de chiles (Capsicum spp.) de Tabasco, Mexico. Cuadernos de biodiversidad, nº 27 (septiembre 2008), 11-22.

Phan, N. T., Biddinger, D. J., Rajotte, E. G., Smagghe, G., Reddy, G. V. P., Ren, Z.-X., & Joshi, N. K. (2025). Pesticide use in integrated pest and pollinator management framework to protect pollinator health. *Pest Management Science, 81*(4), 1691–1696. https://doi.org/10.1002/ps.8582

Prado Urbina, G., Espinoza, L., Carmeconsejer, L., Muñoz, B., Carmeaseso, C., García López, E., & Hebert, V. (2008). *Morphological characterization in situ and germinative capacity in wild populations of Capsicum spp. from the state of Tabasco, Mexico* [Unpublished thesis]. Postgraduate School, Campus Tabasco, Agriculture Food Production Program in the Tropic.

Quaggio, J. A., Mattos, D., Cantarella, H., Almeida, E. L. E., & Cardoso, S. A. B. (2002). Lemon yield and fruit quality affected by NPK fertilization. *Scientia Horticulturae, 96*(1), 151–162.

Rahman, S., Biswas, S. K., Barman, N. C., & Ferdous, T. (2016). Plant extract as selective pesticide for integrated

pest management. *Biotechnological Research, 2*(1), 6–10. https://br.biomedpress.org/index.php/br/article/view/706

Rajpoot, P. K., Singh, D. R., Singh, M., Kumar, S., Yadav, A. K., Tripathi, P., & Kumar, K. (2025). Environmental approaches for reducing pests in chilli (*Capsicum annuum* L.): A review. *International Journal of Advanced Biochemistry Research, 9*(8), 12–17. https://doi.org/10.33545/26174693.2025.v9.i8a.5070

Rumschlag, S. L., Halstead, N. T., Hoverman, J. T., Raffel, T. R., Carrick, H. J., Hudson, P. J., & Rohr, J. R. (2019). Effects of pesticides on exposure and susceptibility to parasites can be generalized to pesticide class and type in aquatic communities. *Ecology Letters, 22*(6), 962–972. https://doi.org/10.1111/ele.13253

Russo, V. M. (2012). Peppers: botany, production and uses. CABI. (Pp 20)

Russu, C. (2023, May 1). *Illegal pesticide use in developing countries: Risks and solutions | Experts' opinions*. DevelopmentAid. https://www.developmentaid.org/news-stream/post/160678/illegal-pesticide-use-in-developing-countries-eo

Sabran, S. H., & Abas, A. (2021). Knowledge and awareness on the risks of pesticide use among farmers at Pulau Pinang, Malaysia. *SAGE Open, 11*(4). https://doi.org/10.1177/21582440211064894

Saldanha, A. V., Gontijo, L. M., Carvalho, R. M. R., Vasconcelos, C. J., Corrêa, A. S., & Gandra, R. (2019). Companion planting enhances pest suppression despite reducing parasitoid emergence. *Basic and Applied Ecology, 41*, 4–14. https://doi.org/10.1016/j.baae.2019.10.002

Shetty, S. S., Deepthi, D., Harshitha, S., Sonkusare, S., Naik, P. B., Kumari, N. S., & Madhyastha, H. (2023). Environmental pollutants and their effects on human health. *Heliyon, 9*(9), e19496. https://doi.org/10.1016/j.heliyon.2023.e19496

Shim, J.-H., Eun, J.-B., Zaky, A. A., Hussein, A. S., Hacimüftüoğlu, A., & Abd El-Aty, A. M. (2023). A comprehensive review of pesticide residues in peppers. *Foods, 12*(5), 970. https://doi.org/10.3390/foods12050970

Shivalingaswamy, T. M., Udayakumar, A., & Mani, M. (2022). Pests and their management in chillies and bell pepper. In M. Mani (Ed.), *Trends in Horticultural Entomology* (pp. 971–982). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0343-4_39

Soujanya, P. L., Sekhar, J. C., Yathish, K. R., Karjagi, C. G., Rao, K. S., Suby, S. B., Jat, S. L., Kumar, B., Kumar, K., Vadessery, J., Subaharan, K., Patil, J., Kalia, V. K., Dhandapani, A., & Rakshit, S. (2022). Leaf damage based phenotyping technique and its validation against fall armyworm, Spodoptera frugiperda (J. E. Smith), in maize. *Frontiers in Plant Science, 13*, 906207. https://doi.org/10.3389/fpls.2022.906207

Souto, A. L., Sylvestre, M., Tölke, E. D., Tavares, J. F., Barbosa-Filho, J. M., & Cebrián-Torrejón, G. (2021). Plant-derived pesticides as an alternative to pest management and sustainable agricultural production: Prospects, applications and challenges. *Molecules, 26*(16), 4835. https://doi.org/10.3390/molecules26164835

Stangarlin, J. R., Kuhn, O. J., & Schwan-Estrada, K. R. F. (2008). Control of diseases of plants by extracts of vegetable origin. *Annual Review of Plant Pathology, 16*, 265–304.

Tavares, W. R., Barreto, M. do C., & Seca, A. M. L. (2021). Aqueous and ethanolic plant extracts as bio-insecticides—Establishing a bridge between raw scientific data and practical reality. *Plants, 10*(5), 920. https://doi.org/10.3390/plants10050920

Tobing, O. L., Mulyaningsih, Y., & Safitri, A. D. (2023). The effect of concentration and frequency of neem leaf extract on aphid attacks on chili plants. *Indonesian Journal of Applied Research (IJAR), 4*(2), 146–158. https://doi.org/10.30997/ijar.v4i2.329

Topuz, A., & Ozdemir, F. (2007). Assessment of carotenoids, capsaicinoids and ascorbic acid composition of some selected pepper cultivars (*Capsicum annuum* L.) grown in Turkey. *Journal of Food Composition and Analysis, 20*(7), 596-602.

Vera-Guzman, A. M., Chavez-Servia, J. L., Carrillo-Rodriguez, J. C., & Lopez, M. G. (2011). Phytochemical evaluation of wild and cultivated pepper (*Capsicum annuum* L. and C. pubescens Ruiz & Pav.) from Oaxaca, Mexico. *Chilean Journal of Agricultural Research, 71*, 578-585. https://doi.org/10.4067/S0718-58392011000400013

Verdadero, F. X. D., Agarap, A. Z., Macatingrao, C. N. E., Ordonez, I. A., Jr., Tavu, L. E. J., Pires, D., & Balendres, M. A. O. (2025). Pesticides in the environment: Benefits, harms, and detection methods. *Science, 7*(4), 171. https://doi.org/10.3390/sci7040171

Wang, L., Kong, L., Wu, F., Bai, Y., & Burton, R. (2005). Preventing chronic diseases in China. *The lancet, 366*, 1821-1824.

Weerasingha, K. A. A. L., & Harris, K. D. (2022). Effect of foliar application of moringa leaf extract on growth and fruit yield of *Capsicum annuum* L. (chilli) cv. MIPC-1. *South Florida Journal of Environmental and Animal Science, 2*(2), 121–132.

Weidenhamer, J. D., Montgomery, T. M., Cipollini, D. F., Weston, P. A., & Mohney, B. K. (2019). Plant density and rhizosphere chemistry: Does marigold root exudate composition respond to intra- and interspecific competition? *Journal of Chemical Ecology, 45*(5–6), 525–533. https://doi.org/10.1007/s10886-019-01073-5

Wenda-Piesik, A., & Piesik, D. (2020). Diversity of species and the occurrence and development of a specialized pest population—A review article. *Agriculture, 10*(11), 541. doi:10.3390/agriculture10110541

Wood, A., Ambridge, L., & Bigger, M. (1996). *A guide to insect pests of Nigerian crops: Identification, biology and control*. NRI.

Wylie, M. R., & Merrell, D. S. (2022). The antimicrobial potential of the neem tree *Azadirachta indica*. *Frontiers in Pharmacology, 13*, 891535. https://doi.org/10.3389/fphar.2022.891535

Yogesh, S., Nagaraju, V., Ajrawat, A., & Mahesh, P. (2025). Pest and disease management in fruit crops: Strategies for sustainable production. *Agri Magazine, 2*(1), 221–225.

Yousefi, M., Marja, R., & Barmettler, E. (2024). The effectiveness of intercropping and agri-environmental schemes on ecosystem service of biological pest control: A meta-analysis. *Agronomy for Sustainable Development, 44*, 15. https://doi.org/10.1007/s13593-024-00947-7

Zarina, B., & Shahina, F. (2010). Research work carried out on the management of root-knot nematode diseases in Pakistan. *Pakistan Journal of Nematology, 28*(2), 153-239.

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