CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Push-Pull systems as a nature-based solution for sustainable pest management in chili pepper agroecosystems

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Received: 20 February 2026; Accepted: 9 June 2026, Available online: 3 August 2026. doi:10.4067/S0718-58392026000500765

ABSTRACT

Intensified agricultural practices and climate change have both increased pest pressure on crops; therefore, many farmers are reliant on the application of synthetic pesticides, which have harmful environmental effects. The push-pull method of pest management, which alters insect behavior by manipulating their responses to their environment, is a nature-based solution that helps produce a healthier, more sustainable food production system. This study investigated the effects of push-pull systems on pesticide application frequency, pest management efficiency, and chili pepper (*Capsicum annuum* L. var. *annuum*) productivity. The field experiment was conducted at the Horticulture Seeds Research Centre in West Java, Indonesia, from August 2024 to March 2025. A randomized complete block design with 3 treatments and 7 replicates was used to evaluate two push-pull systems: Aromatic intercrops, such as coriander (*Coriandrum sativum* L.) and celery (*Apium graveolens* L.), plus light traps, and traditional chemical-based pest management. Data were analyzed using ANOVA followed by least significant difference (LSD) test at the 5% significance level ($P < 0.05$). The push-pull system significantly reduced total fruit damage caused by pests and diseases to 27.77%-28.91%, compared with 37.48% under traditional methods ($P \leq 0.05$). Pest populations remained below the economic threshold, eliminating the need for insecticide application. In addition, plant growth and yield components improved under the push-pull system, increasing yields up to 28.45% compared with the farmer-managed system ($P \leq 0.05$). Similar microclimatic conditions across treatments indicate that these differences were mainly driven by ecological interactions rather than abiotic factors. This study demonstrated that push-pull systems can simultaneously reduce pesticide use, suppress pest populations, and enhance crop productivity in chili pepper production systems.

Keywords: Agroecosystem resilience, *Capsicum annuum*, celery, coriander, nature-based solutions, sustainable intensification.

INTRODUCTION

Global food production systems face increasing challenges due to rapid population growth, climate change, and increased intensity of food production. Increased demand for food products worldwide has increased the rate of expansion of food crops. Pesticide applications have increased in response to greater intensification of food production and as a result of the intensified application of chemicals for pest management (FAO, 2022). Pests are affected by climate change, which influences the occurrence and population trends of pests; this results in greater risk from pests and lessens the long-term effectiveness of traditional chemical methods for pest control (Deutsch et al., 2018; IPCC, 2022). All these factors present challenges to food production systems, the environment, human health, and ecosystem stability (Dzvene and Chiduza, 2024).

The extensive and widespread application of synthetic pesticides in agriculture is a source of many negative impacts on the environment, including reductions in biodiversity, degradation of both ground and surface water resources, and disruptions to ecological functions that are vital for the maintenance of agroecosystems (Sánchez-Bayo and Wyckhuys, 2019). As a result, international policy initiatives (e.g., FAO, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], Intergovernmental Panel on Climate Change [IPCC]) and scientific reviews/evaluations have identified the urgent need for ecologically based and climate-resilient approaches to pest management that decrease chemical dependency on pesticides while increasing the level of provision of ecosystem services (FAO, 2022; IPBES, 2023). Nature-based solutions (NbS) are considered an effective way to concurrently address issues of food security, biodiversity preservation, and environmental sustainability (Seddon et al., 2020).

A NbS referred to as "push-pull" represents an alternative pest management strategy that utilizes plant volatiles to modify insect behavior through repellents and attractants. Plants used in conjunction with the main crop produce volatile compounds that serve as repellents to crop-feeding insects ("push"), while other stimuli may be used to attract insects away from the crop ("pull"). (Khan et al., 2018; Mala et al., 2020). In the present study, coriander (*Coriandrum sativum* L.) was used as a push component because of its repellent volatile compounds, whereas a light trap was used as the pull component to attract insect pests away from the chili crop. By exploiting these behavioral responses, push-pull strategies can reduce reliance on synthetic pesticides and provide an ecologically based approach to pest management.

In selecting coriander and celery (*Apium graveolens* L.), two aromatic plants, for use as companion crops in the push-pull system, the reason is their documented release of volatile organic compounds that inhibit pest behavior and prevent them from locating hosts and laying eggs. Terpene-rich aromatic plants can disrupt pest navigation cues by making it difficult to locate a plant or herb, which will make it difficult to lay eggs. They are an additional means of increasing habitat complexity and adding functional diversity to an agricultural ecosystem, providing habitat for beneficial insects (Dikr, 2022; Qasim et al*.,* 2024; Gunaeni et al*.,* 2024). The compatibility of coriander and celery in horticultural agroecosystems is one of the reasons they are considered suitable for growing together with chili peppers, as they do not compete significantly for resources and allow ecological regulation without limiting plant growth (Gunaeni et al., 2024).

Light traps serve as an additional non-chemical method to attract nocturnal adult moths to capture them before oviposition and therefore reduce recruitment of pests into local populations at the landscape level (Abbas et al*.,* 2019; Rhainds, 2024; Murtiningsih et al*.,* 2024). Combining aromatic intercrops and light traps creates a streamlined behavioral push-pull approach that reduces dependence upon chemical pesticides and promotes the application of Ecosystem-Based Pest Management (EBP) principles within a regulatory governance context.

Push-pull approaches have been shown in empirical studies to both reduce the numbers of pest populations and increase the number of active natural predators, which improves the overall effectiveness of Integrated Pest Management (IPM) approaches (Khan et al*.,* 2018; Alkema et al*.,* 2019). However, most push-pull research has primarily concentrated on cereal-based or staple cropping systems, with a main focus on yield protection and pest suppression. Relatively little attention has been given to high-value horticultural crops such as chili (*Capsicum annuum* L. var. *annuum*), which are especially susceptible to pest pressure and pesticide overuse under tropical and subtropical conditions (Park et al*.,* 2024; Rajpoot et al*.,* 2025).

More critically, current studies rarely frame the push-pull system within an environmental management or ecosystem services framework. Ecological functions such as biological pest regulation, functional biodiversity enhancement, and chemical risk reduction are often seen as secondary benefits rather than core system outcomes (Munawar et al*.,* 2023; Atnafu and Wobale, 2025). As a result, the potential of the push-pull system to act as an NbS supporting environmental governance, climate adaptation, and ecosystem-based management remains underexplored.

Although push-pull technology has been successfully applied in several cropping systems, information regarding its implementation in chili pepper agroecosystems remains limited. In particular, the effectiveness of combining coriander as a repellent ("push") component and a light trap as a "pull" component under field conditions has not been thoroughly evaluated. Moreover, limited information is available on how this strategy affects plant growth, pest abundance, pest infestation intensity, pesticide reduction, and chili pepper yield (IPCC, 2022). Therefore, this study aimed to determine whether integrating coriander as a push component and a light trap as a pull component can simultaneously enhance plant growth, suppress pest populations and infestation intensity, reduce pesticide use, and improve chili pepper yield under field conditions.

In light of the limitations of low-input and behavior-based pest management strategies such as push-pull technology in providing ecosystem service benefits and favorable environmental outcomes in horticultural systems, this study evaluates the impact of these systems on the use of pesticides, effectiveness in controlling pests, and crop yields in chili pepper farming.

It was hypothesized that the integration of coriander and light traps would suppress pest abundance and infestation intensity, reduce pesticide use, and enhance plant growth and chili pepper yield compared with conventional management practices.

MATERIALS AND METHODS

Climatic conditions in the location study

The study was conducted in a chili pepper (*Capsicum annuum* L. var. *annuum*) agroecosystem under open-field conditions at the Horticultural Seed Center, in Lembang (-6.7844 S, 107.6231 E), West Java, Indonesia, during the main growing season of 2024-2025. The experimental site was characterized by a tropical climate with distinct wet and dry seasons, representative of intensive horticultural production systems in the Horticultural Seed Center, located at 1250 m a.s.l., with humidity ranging from 64% to 84%, with average annual temperatures and precipitation around 25-26 °C and 1900 mm, respectively. The soil type at the site was Andosol, with an average pH ranging from 5.0 to 6.0. Air temperature and relative humidity were monitored during the experiment, data loggers were placed in each treatment (B-SIDE BTH 81, BSIDE, Shenzhen, Guangdong, China).

Field trial

The experiment was arranged in a randomized complete block design (RCBD) with three pest management treatments and seven replicates (blocks). Each block contained all treatments, and treatment allocation within each block was randomized. The treatments consisted of: Chili pepper intercropped with coriander (*Coriandrum sativum* L.) combined with a light trap (push-pull system 1) (T1), chili pepper intercropped with celery (*Apium graveolens* L.) combined with a light trap (push-pull system 2) (T2), and conventional farmer practice (T3). Each experimental plot measured 23.5 m² and contained 76 chili pepper plants. In the intercrop treatments, coriander or celery was established within the chili pepper plots according to the treatment layout. To minimize interference among treatments, adjacent plots were separated by four rows of maize (*Zea mays*) that served as buffer rows.

To reduce damage from pests and diseases, 'Kencana' chili seedlings were cultivated in a protected nursery. The seeds were placed in a nursery with a screen before being immersed in warm water (50 °C) for 20 min. Seedlings were moved into experimental beds with reflective plastic mulch 5 wk after sowing. The land was prepared manually, beginning with plowing and forming beds arranged with a spacing of 50 × 70 cm. The basic fertilizer was chicken manure at 20 t ha^{-1} applied along with other fertilizers, including NPK at 1000 kg ha^{-1}. Irrigation was conducted twice weekly by manual watering, depending on rainfall conditions. Staking was performed at 2-3 wk after transplanting to support plant growth, and pruning of side shoots was conducted periodically to maintain plant architecture and improve air circulation. Weed control was carried out manually every 2 wk. All agronomic practices were kept consistent across treatments, except for pest management interventions, which consisted of the push-pull system and conventional chemical control. Two light traps (locally manufactured traps, West Java, Indonesia) were installed in each experimental plot assigned to the push-pull treatments (T1 and T2) at the time of chili pepper seedling transplantation. The traps were positioned on opposite sides of the plot (left and right margins) to ensure uniform attraction coverage. The conventional control treatment (T3) did not include light traps (Figure 1). Each trap was equipped with a solar-powered lamp emitting wavelengths of 365-400 nm, which operated using a 5.5 V solar panel connected to a 3.7 V Panasonic 18650 rechargeable battery and a 0.5 W UV-LED lamp. The light source was positioned above a plastic basin containing 2 L detergent (Rinso, Unilever, UK) to retain attracted insects and was replaced at each observation to maintain trapping efficiency. Trap height was periodically adjusted to keep the light source above the crop canopy. The number of lepidopteran moths caught in traps was counted separately and recorded two times per week to prevent damage of moth. Insecticide applications in the push-pull treatments (T1 and T2) were guided by damage-based control thresholds and applied only when crop injury exceeded ≥ 25 moth trap^{-1} wk^{-1} for lepidopteran pests (*Spodoptera litura* and *Helicoverpa armigera*), following integrated pest management recommendations (Murtiningsih et al., 2024). In contrast, the conventional treatment (T3) followed local farmer practices, with spinetoram applied at a rate of 2 mL L^{-1} water at 7 d intervals throughout the growing season, irrespective of pest infestation levels. Species identification of key pests (*S. litura* and *H. armigera*) was confirmed based on widely recognized morphological descriptions in agricultural pest management literature (Capinera, 2020).

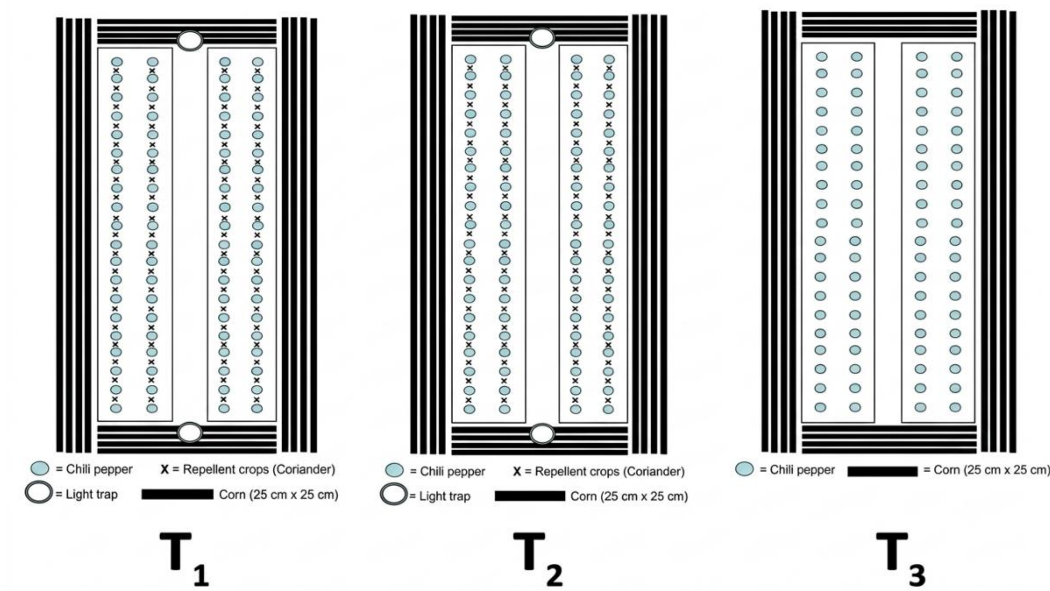

Figure 1. Experimental field layout including intercrop design, block structure, buffer distances, and light trap placement.

Parameter observation

Ten plants from each experimental plot were selected as subsamples using a U-shaped sampling pattern to ensure representative coverage of the entire plot while minimizing edge effects. The selected plants were monitored weekly starting from 14 d after planting (DAP). For statistical analysis, measurements from the 10 sampled plants were averaged to obtain a single plot-level value, which served as the experimental unit. These include plant height, canopy width, and other plant growth-related characteristics. Pest damage was monitored on a weekly basis based on the symptoms of damage observed on the plants and fruits. The intensity of crop damage caused by both pests was determined using the following formula:

$$P = \frac{\sum(n \times v)}{N \times Z} \times 100\%$$

in this formula P represents plant damage intensity (%); v is damage value (score) for each plant determined by the area of its leaves that has been attacked, specifically: 0 (no damage), 1 (> 0%-≤ 20%), 3 (> 20%-≤ 40%), 5 (> 40%-≤ 60%), 7 (> 60%-≤ 80%), 9 (> 80%); n represents the quantity of plants with the same value for v (plant damage); Z represents the greatest damage score (9); and N represents the quantity of plants observed. Additionally, the incidence of fruit damage due to pests and disease attacks was assessed from harvested fruits of 10 sample plants per plot at each harvest, calculated using the following formula:

$$\text{Fruit damage intensity (\%)} = \frac{\text{Number of infected fruits per plot}}{\text{Total number of fruits per plot}} \times 100\%$$

Fruit yield per plot was recorded during the harvest period and extrapolated to determine the mean fruit yield per hectare. In addition, the morphological characteristics of the fruit, such as fruit weight (g), length (cm), and diameter (mm), were recorded during the harvest period. For fruit trait measurements, 10 fruits were randomly sampled from each plot at each harvest. The average value per plot was used as the experimental unit for statistical analysis. The number of insecticide applications for all the treatments was recorded. The efficiency of pesticide application was calculated using the following formula:

$$E (\%) = [(TA - TT)/TA] \times 100\%$$

In this formula, E represents the efficiency of pesticide application, TA corresponds to the number of pesticide applications in control, and TT is the number of pesticide applications in a certain treatment.

Data analysis

Statistical analysis was performed using the PKBT-STAT 1.0 software (Center for Tropical Horticulture Studies, IPB University, Bogor, Indonesia). Data were analyzed using ANOVA based on a randomized complete block design (RCBD). When significant differences were detected, treatment means were separated using the least significant difference (LSD) test at the 5% significance level ($P < 0.05$). For variables measured repeatedly over time, analyses were conducted separately for each observation date using ANOVA. Percentage data were analyzed after appropriate transformation when necessary to meet assumptions of normality and homogeneity of variance. Count data were also analyzed using ANOVA after verification of model assumptions.

RESULTS AND DISCUSSION

Plant growth characteristics (plant height, canopy width, and branching)

The treatments used in this study affected many of the growth characteristics of the chili peppers, including their overall plant height, canopy spread, and how many branches grew from each plant (Figures 2, 3, and 4). Compared to the conventional methods for controlling pests, the push-pull method of pest control significantly improved the vegetative vigor of the chili pepper plants. More specifically, compared to the conventional methods of controlling pests, compared with conventional pest management, the push-pull system significantly increased plant height, canopy size, and number of branches per plant ($p < 0.05$), indicating improved vegetative growth. However, nonsignificant Time × Treatment interaction was detected, suggesting that the effect of the treatments on plant growth was consistent across all observation periods. Of the two push-pull systems tested, push-pull 2 (celery + light traps) had the largest number of branches plant^{-1} (12.6), and push-pull 1 (coriander + light traps) had the second largest number of branches plant^{-1} (12.1). Conventional management systems produced the fewest branches per plant (11.7). All three of these measurements (number of branches plant^{-1}, plant height, and canopy width) were also significantly larger for the push-pull systems than for the conventional systems of pest management. These results demonstrate an increased ability of the crops grown using the push-pull systems to utilize resources and increase photosynthesis over those grown using conventional systems of pest management. Since the plant heights and canopy widths of the plants managed with the push-pull system were no smaller than those managed using the conventional methods, it is unlikely that the push-pull system restricted plant growth or created resource competition for the chili peppers.

The increase in branch numbers of the plants grown using the push-pull systems may have been a result of the indirect effects of the push-pull systems on the crops, such as lower levels of biotic stress and lower pest pressure, both of which may occur at the early stages of crop development and contribute to the production of additional branches. Reducing herbivory in crops is advantageous to retaining photosynthesis and hormone regulation with increased ability to produce more assimilates for lateral growth instead of repairing tissues (Blundell et al*.,* 2020; Jaiswal et al*.,* 2022). Furthermore, aromatic intercrops in a diversified cropping system may create a more stable microclimate and improve soil biological processes, promoting healthy root development while preventing excessive canopy development, which may increase the risk of disease (Zhang et al*.,* 2021; Wang et al*.,* 2025). These studies demonstrate that push-pull farming systems can provide ecological pest management and chemical reduction while supporting long-term, stable plant structure, thus offering a multifaceted approach to sustainable agriculture.

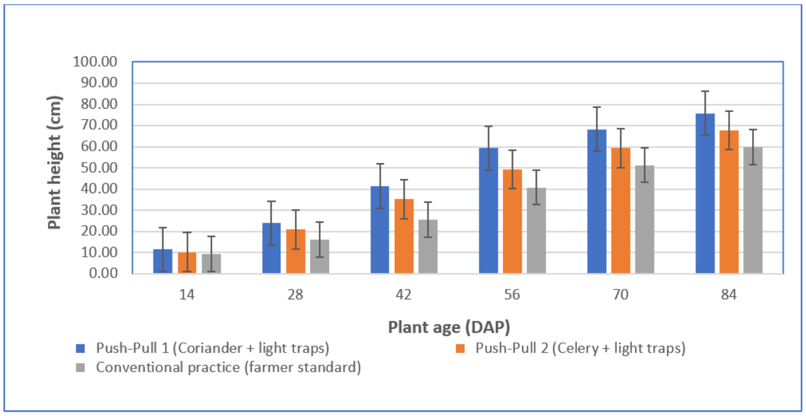

Figure 2. Plant height of chili pepper under different push-pull systems. DAP: Days after planting.

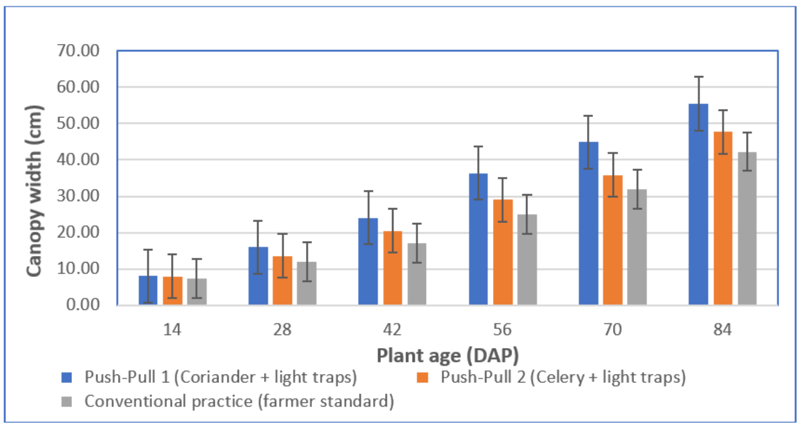

Figure 3. Canopy width of chili pepper under different push-pull systems. DAP: Days after planting.

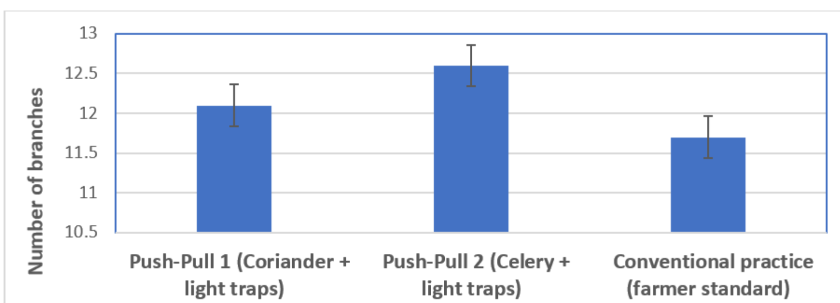

Figure 4. Canopy width of chili pepper under different push-pull systems.

Microclimatic conditions

Air temperature and relative humidity were monitored during the experiment and are presented as descriptive environmental variables. Only minor variations were observed among treatments, indicating relatively uniform microclimate conditions across the experimental plots. However, they consistently ranged similarly during the entire growing season (Table 1). Air temperature averaged from 25.06 to 26.36 °C. Relative humidity averaged from 63.90% to 84.38%. The highest mean relative humidity was found in push-pull 2, while the highest mean air temperature was found in conventional practices. Extreme microclimatic conditions were not present that would independently impede chili pepper growth or insect pest activity.

Table 1. Microclimatic conditions (air temperature and relative humidity) under different push-pull management systems. Data loggers were placed in each treatment.

	Temperature (°C)			Humidity (%)		
Treatments	Minimum	Maximum	Average	Minimum	Maximum	Average
T1. Push-pull 1 (coriander + light traps)	16.76	42.94	25.8	27.02	92.68	63.9
T2. Push-pull 2 (celery + light traps)	13.06	43.18	25.06	45.2	99.96	84.38
T3. Conventional practice (farmer standard)	13.24	44.58	26.36	37.62	99.46	80.02

Therefore, given the relatively similar microclimatic conditions across treatments, differences in pest pressure, plant growth, and yield observed in the push-pull systems may be associated with ecological interactions arising from system components, although other contributing factors cannot be fully excluded. While slightly elevated humidity values in push-pull systems may be indicative of greater vegetative density and/or a more complex canopy structure than conventional practices, both factors have been shown to create microenvironments that buffer microenvironmental conditions, decrease solar radiation exposure, increase microhabitat stability, and contribute to ecosystem services such as biological control and the presence/activities of beneficial insects. The lack of large-scale microclimatic differences further supports this interpretation; that is, the observed reductions in pest populations, disease levels, and crop yields can be attributed to behaviorally driven pest regulation and reduced chemical disruption, rather than being caused by abiotic environmental factors. This pattern is consistent with both agroecological and nature-based approaches for managing pests, in that they both recognize the role of functional biodiversity as an essential component in maintaining ecosystem services; specifically, those providing biological control of pests (Altieri et al., 2015; Kremen and Merenlender, 2018; Tamburini et al*.*, 2020).

Pest and disease suppression

Damage to fruits due to insect pests and diseases was greatly reduced under push-pull systems relative to conventional practice. This is in line with the further suppression of thrips damage throughout the growing season (Figure 4) and the reduction of lepidopteran moth populations trapped by light traps (Figures 5 and 6). Moreover, the push-pull systems eliminated the need to apply insecticides, which represents a 100% reduction relative to conventional practice (Table 2). Overall, the damage to fruits by insects was reduced to 18.35% under push-pull 1 and 19.61% under push-pull 2 relative to 22.31% under conventional practice (Table 3). Fruit fly damage was reduced by up to 21% under push-pull 1. Even as damage due to fruit borer did not differ significantly between treatments, the reduction of damage due to various pests resulted in significantly lower damage due to insects under the push-pull system. Similarly, disease damage was reduced under push-pull systems relative to conventional practice, with the total disease-infected fruits being reduced to 9.30%-9.42% under push-pull systems relative to 15.17% under conventional practice. These findings are also in line with the growing body of knowledge indicating that push-pull cropping systems, aside from suppressing populations of insect pests, can also result in lower disease incidence and mycotoxin contamination (Njeru et al*.,* 2020), and lower relative abundance of disease-associated genera, indicating a further ecological mechanism by which push-pull intercropping systems can result in the mitigation of crop disease (Jalloh et al*.,* 2024). The reduction in pest pressure and improved production efficiency observed in this study are consistent with recent evidence showing that diversified cropping systems enhance ecological regulation through increased activity of natural enemies and strengthened ecosystem services (Jasrotia et al*.,* 2023; Lenné and Wood, 2024).

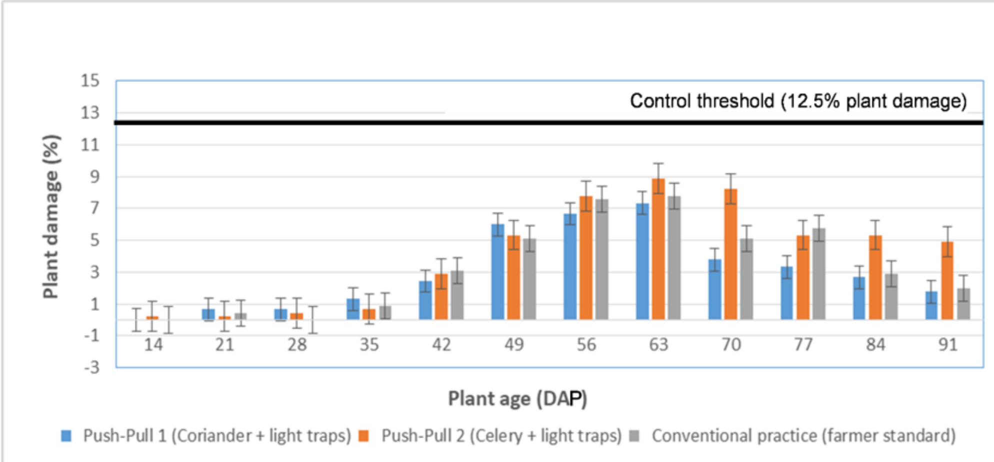

Figure 5. Thrips-induced plant damage (%) in chili pepper under different push-pull systems. DAP: Days after planting.

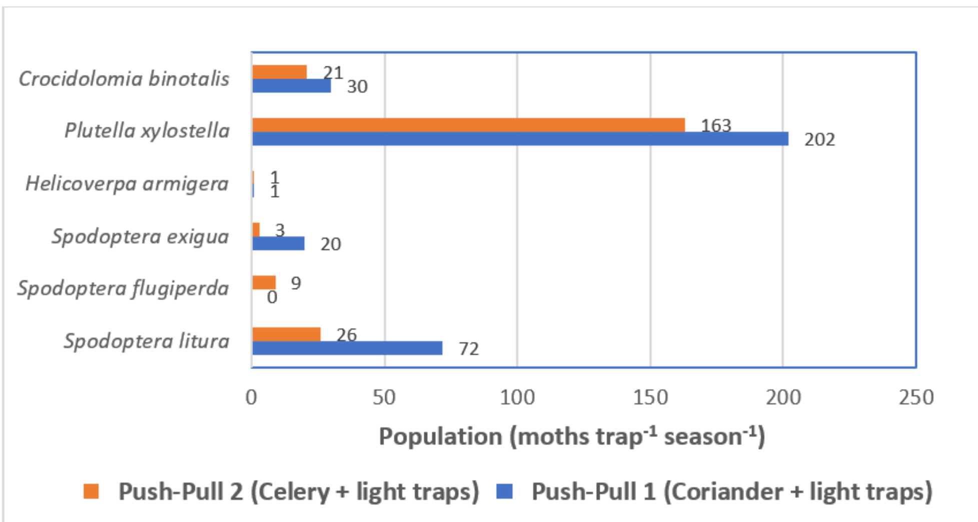

Figure 6. Abundance of lepidopteran moths captured by light traps under different push-pull systems in chili pepper.

Table 2. Insecticide application frequency and reduction under different push-pull systems in chili cultivation. *Conventional practice refers to farmer-managed chili cultivation relying on insecticide-based pest control.

Treatment	Number of insecticide applications per season	Reduction in insecticide use (%)
T1. Push-Pull 1 (coriander + light traps)	0	100
T2. Push-Pull 2 (celery + light traps)	0	100
T3. Conventional practice (farmer standard)*	12	0

Table 3. Fruit damage by major insect pests and diseases under different push-pull systems in chili pepper. Values followed by different letters within the same column are significantly different according to the LSD ($P \leq 0.05$).

Treatment	Fruit damage by fruit flies	Fruit damage by the fruit borer	Total insect-damaged fruits	Fruit damaged by Anthracnose diseases	Fruit damaged by bacterial diseases	Total disease-infected fruits	Total damaged fruits by pests and diseases
	%	%	%	%	%	%	%
T1. Push-pull 1 (coriander + light traps)	14.17[b]	4.18[a]	18.35[b]	3.57[b]	5.86[b]	9.42[b]	27.77[b]
T2. Push-pull 2 (celery + light traps)	15.63[ab]	3.98[a]	19.61[ab]	3.38[b]	5.92[b]	9.30[b]	28.91[b]
T3. Conventional practice (farmer standard)	17.95[a]	4.37[a]	22.31[a]	5.49[a]	9.68[a]	15.17[a]	37.48[a]
LSD ($p \leq 0.05$)	3.59	0.58	3.76	1.18	1.22	2.21	4.97
CV, %	15.48	9.57	12.83	19.43	11.71	13.44	10.86

Previous studies have shown that light traps are effective in catching nocturnal lepidopteran moths, which enables to understand their behavioral responses to artificial light sources and apply this method to study pest management (Bhusal and Chapagain, 2020; Murtiningsih et al., 2024; Yang et al., 2024). Consistent with this basis, weekly monitoring in the present study indicated that moth populations in the push-pull treatments equipped with light traps consistently remained below the action threshold (≤ 25 moths trap^{-1} wk^{-1}). Because light traps were not deployed in the conventional treatment, trap-catch data were not directly comparable between treatments. Push-pull 1 recorded the fewest moth captures (0-17 moths trap^{-1} wk^{-1}), followed by push-pull 2 (0-7 moths trap^{-1} wk^{-1}) (Figures 6 and 7). Moreover, the effectiveness of the push-pull system in eliminating the need for insecticides contrasts with the 12 applications per season required for the conventional system (Table 2). These findings are consistent with previous evidence that the inclusion of light traps in diversified farming systems contributes to the control of *Spodoptera frugiperda* via reduced adult population abundance and indirectly limits the development of larvae via habitat-based ecological processes (Gebreziher and Gebreazgaabher, 2024). The findings suggest that the push-pull system controls pests in chili pepper production via reduced insect abundance, reduced disease incidence, and reduced insecticide use. The reduced thrips infestation in the push-pull system illustrates the effectiveness of diversified farming systems in disrupting the ability of pests to locate hosts and feed, particularly in the early stages of crop development. The reduction in pest pressure may be associated with volatile emissions from aromatic intercrops and the capture of nocturnal adults by light traps. However, these mechanisms were not directly measured in this study and are therefore proposed as potential explanations rather than confirmed processes. Together, these methods modify pest movement patterns within the farm ecosystem (Gunaeni et al., 2024; De Jorge et al., 2024).

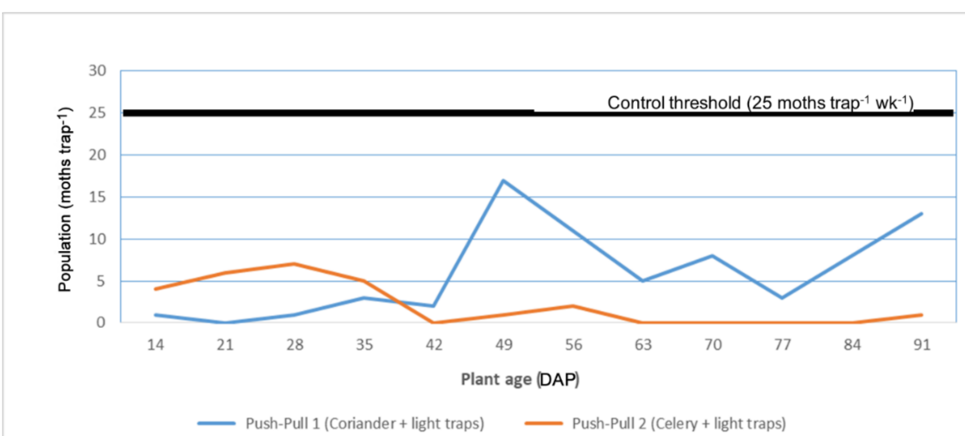

Figure 7. Weekly abundance of lepidopteran moths captured per light trap under different push-pull systems in chili pepper. DAP: Days after planting.

Decreases in fruit fly damage and insect-damaged fruit are in line with current findings, which suggest that behavioral control methods for managing pests reduce oviposition and establishment of larvae through multiple, rather than a single, target pathway (Luttermoser et al*.,* 2023). Although fruit borer damage alone did not significantly change due to the effects of this method for managing pests at the agroecosystem level, when looking at how many different types of pests were managed using this method. Total damage was included as a predefined response variable in this study to capture the integrated impact of pest abundance and infestation intensity. The push-pull treatments resulted in a significant reduction in this parameter compared with the conventional system. This demonstrates that pest management is best assessed by evaluating it as a whole (i.e., the agroecosystem) rather than separately by pest type.

The lower incidence of disease observed in the push-pull plots reflects indirect ecosystem benefits as a result of reducing pest populations within an agricultural area. By reducing the number of insects damaging crops, there are fewer locations for pathogens to enter the plant, and therefore less opportunity for vectors to mediate the transmission of pathogens such as those causing anthracnose and bacterial fruit diseases. Similar types of pest-disease relationships have been identified in ecologically enhanced cropping systems where reduced chemical use has contributed to improved crop health, crop resilience, and crop yield stability (Blundell et al., 2020; Jaiswal et al*.,* 2022).

Push-pull is a multi-faceted insect pest management approach that reduces reliance on insecticides through ecological mechanisms. In this study, it acted as a nature-based solution (NbS) by reducing pest pressure and improving crop performance under field conditions. Broader ecological benefits such as long-term ecosystem resilience and reduced environmental pollution are potential outcomes that were not directly assessed in this study. A meta-analysis conducted by Yousefi et al. (2024) indicated that diversified plantings (including intercropping and agri-environmental schemes) greatly affect arthropod communities and enhance biological control of pests. The positive relationship between suppression of moths (Figures 6 and 7), reduction in fruit damage (Table 3), and lack of insecticide application (Table 2) demonstrates their functionally effective performance. The slightly superior performance of push-pull 1 may be due to greater repellency or disruption of host location by volatile compounds emitted by coriander. Overall, these findings support long-term evidence that push-pull systems maintain pest suppression with minimal risk of adaptation, highlighting their importance in sustainable intensification and climate-resilient agriculture (Midega et al*.,* 2017; Hailu et al., 2018; Luttermoser et al*.,* 2023).

Yield components and fruit attributes of chili pepper under push-pull systems

The use of push-pull management systems significantly improved the yield components and quality of chili pepper fruits (Table 4). The best results for flower and fruit production were recorded by push-pull 1 for both flowers (181.3 plant^{-1}) and fruits (115.6 plant^{-1}), and then by push-pull 2, with significantly lower values for traditional practices. Parameters for fruit morphology, i.e., fruit diameter, length, and weight, were maximized by push-pull 1.

Table 4. Effects of push-pull systems on reproductive traits and fruit characteristics of chili pepper. Values followed by different letters within a column are significantly different according to the LSD ($P \leq 0.05$).

Treatment	Number of flowers	Number of fruits	Fruit diameter	Fruit length	Fruit weight
	Nr	Nr	mm	cm	g
T1. Push-pull 1 (coriander + light traps)	181.30[a]	115.60[a]	6.43[a]	13.60[a]	59.48[a]
T2. Push-pull 2 (celery + light traps)	177.20[a]	112.10[ab]	6.14[b]	13.12[b]	56.36[b]
T3. Conventional practice (farmer standard)	137.80[b]	82.50[b]	6.22[ab]	13.13[b]	54.77[c]
LSD (5%)	15.08	10.41	0.28	0.30	1.11
CV, %	14.54	20.17	3.11	1.53	1.34

Marketable yield was determined from total fresh weight per experimental plot (23.5 m²) and extrapolated to a hectare basis (t ha^{-1}) using a standard area conversion (10 000 m² = 1 ha) and 75% of the effective cultivated area (excluding spacing between plots and maize border rows). Using this calculation, push-pull 1 produced 22.79 t ha^{-1} and push-pull 2 produced 21.94 t ha^{-1}, ensuring consistency between plot-level measurements and reported yield per hectare, respectively, compared to conventional practice (Table 5). These results are consistent with earlier studies conducted in the field that showed push-pull technology improves crop productivity and stability relative to conventional crop production systems (Ndayisaba et al*.,* 2020; Guera et al*.,* 2021; Sileshi et al*.,* 2025). These improvements may be associated with enhanced ecosystem regulation within the push-pull system rather than being solely driven by increased external input levels. Push-pull technology controls pest populations below damaging levels due to changes in pest movement, host location, and population levels.

Table 5. Effect of push-pull systems on marketable yield and productivity of chili pepper. Values followed by different letters within a column are significantly different according to the LSD ($P \leq 0.05$). Yield increase was calculated relative to conventional farming practice. yield per hectare values were calculated based on 75% of the effective cultivated area, excluding spacing between plots and maize border rows.

Treatment	Healthy fruits	Yield	Yield increase relative to conventional practice
	kg 23.5 m^{-2}	t ha^{-1}	%
T1. Push-pull 1 (coriander + light traps)	57.96[a]	22.79[a]	28.45
T2. Push-pull 2 (celery + light traps)	55.93[a]	21.94[a]	23.63
T3. Conventional practice (farmer standard)	38.87[b]	17.74[b]	-
LSD (5%)	4.83	5.15	
CV, %	6.52	5.22	

The decrease in pest pressure also has indirect effects on the health of crops. The decrease in insect pressure provides less of a way for insects to enter into crops as disease vectors and therefore decreases the amount of disease present and the stability of crop yield. While there was a range of responses to the push-pull technology among individual pest species, the overall regulation of all pest species resulted in a decrease in biotic pressure during the most critical growth stages of the crop. This allowed for better crop health as evidenced by higher retention of flowers, fruit set, and better allocation of resources toward the development of fruits. Similar relationships have been found between ecological pest control, crop health, and yield stability in other agroecosystem types (Karp et al*.,* 2018; Savary et al*.,* 2019; Tamburini et al*.,* 2020).

In addition, the close relationship between pest management and reduced pressure from diseases and increased yields supports the push-pull system as a means to provide ecosystem services, including biological regulation, chemical usage reduction, and yield stability. Elimination of total insecticide application further supports the push-pull system as an NbS that is able to decouple chemical use from agricultural productivity (Midega et al*.,* 2017; FAO, 2022; IPBES, 2023).

Beyond the effects on the regulation of pests and yield, the results also indicate the broader environmental impacts of push-pull systems as NbS for chili pepper production. The results support the broader environmental impacts associated with utilizing push-pull systems as an NbS for chili pepper production. Reducing the use of synthetic pesticides reduces chemical use, reduces the risk of soil and water contamination, and reduces negative impacts on non-target species. Push-pull systems encourage ecosystem-based pest regulation, and this encourages biodiversity while maintaining crop yields. Further research is needed to evaluate the performance of push-pull systems under different climatic conditions and across diverse agroecosystems better to understand their wider applicability in chili pepper production.

CONCLUSIONS

Push-pull systems significantly improved crop productivity in chili pepper through reductions in pest pressure and increases in marketable yield under field conditions. Using aromatic intercrops combined with light traps reduced total fruit damage from pests and diseases to 27.77%-28.91%, compared to 37.48% with traditional methods, while also eliminating insecticide use (a 100% reduction).

Microclimate conditions were similar for each treatment and it was found that ecological processes – primarily pest control through behavior and reduction of pesticide applications – are responsible for the majority of the increased yield due to the push-pull system; and from an environmental management perspective, push-pull systems represent a viable alternative to conventional pesticide based methods for agricultural production, which has the potential to reduce pesticide dependency, minimize environmental risks, and enhance the resilience of ecosystems in agroecological systems.

The research supports three approaches to agricultural production in tropical regions: (a) Sustainable intensification; (b) integrated pest management; and (c) climate-resilient agriculture. Push-pull systems improved pest management and increased chili pepper productivity under the field conditions studied, as indicated by reduced pest pressure and higher marketable yield compared with conventional practices.

Author contribution

Conceptualization: N.G., W.S., T.K.M., B.K.U. Methodology: N.G., W.S., T.K.M. Software: R.M., Y.S., T.K.M. Validation: W.S., B.K.U., Y.S., A.K.K. Formal analysis: W.S., T.K.M., R.M., B.K.U. Investigation: N.G., W.S., T.K.M. Resources: E.K., H., E.D. Data curation: A.N., A.K.K. Writing-original draft: N.G., W.S., T.K.M., B.K.U., E.D. Writing-review & editing: W.S., R.M., Y.S. Visualization: W.S., T.K.M., Y.S., A.N., H. Supervision: W.S., B.K.U. Project administration: B.K.U., T.K.M. Funding acquisition: E.K. All co-authors reviewed the final version and approved the manuscript before submission.

Acknowledgements

The author would like to thank the Horticultural Seed Center for providing material to support this research.

References

Abbas, M., Ramzan, M., Hussain, N., Ghaffar, A., Hussain, K., Abbas, S., et al. 2019. Role of light traps in attracting, killing, and biodiversity studies of insect pests in Thal. Pakistan Journal of Agricultural Research 32(4):684-690. doi:10.17582/journal.pjar/2019/32.4.684.690.

Alkema, J.T., Dicke, M., Wertheim, B. 2019. Context-dependence and the development of push-pull approaches for integrated management of *Drosophila suzukii*. Insects 10(12):454. doi:10.3390/insects10120454.

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A. 2015. Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development 35:869-890. doi:10.1007/s13593-015-0285-2.

Atnafu, D., Wobale, Z. 2025. A Review of push-pull technology's effect on the management of fall armyworms (*Spodoptera frugiperda*) in Ethiopian maize (*Zea mays*) production. Journal of Plant Sciences 13(6):201-209. doi:10.11648/j.jps.20251306.11.

Bhusal, S., Chapagain, E. 2020. Threats of fall armyworm (*Spodoptera frugiperda*) incidence in Nepal and its integrated management — A review. Journal of Agriculture and Natural Resources 3(1):345-359. doi:10.3126/janr.v3i1.27186.

Blundell, R., Schmidt, J.E., Igwe, A., Cheung, A.L., Vannette, R.L., Gaudin, A.C.M., et al. 2020. Organic management promotes natural pest control through altered plant resistance to insects. Nature Plants 6(5):485-491. doi:10.1038/s41477-020-0656-9.

Capinera, J.L. 2020. Handbook of vegetable pests. 2nd ed. Academic Press, Cambridge, Massachusetts, USA.

De Jorge, C., Kossmann, A., Hummel, H.E., Gross, J. 2024. Evaluation of a push-and-pull strategy using volatiles of host and non-host plants for pest management. Frontiers in Plant Science 15:1375495. doi:10.3389/fpls.2024.1375495.

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., Battisti, D.S., Merrill, S.C., Huey, R.B., et al. 2018. Increase in crop losses to insect pests in a warming climate. Science 361(6405):916-919. doi:10.1126/science.aat3466.

Dikr, W. 2022. Role of intercropping some aromatic and medicinal plants with fruit and vege crops, a review. Global Academic Journal of Agriculture and Biosciences 4(2):22-30. doi:10.36348/gajab.2022.v04i02.002.

Dzvene, A.R., Chiduza, C. 2024. Application of biofertilizers for enhancing beneficial microbiomes in push-pull cropping systems. Bacteria 3(4):271-286. doi:10.3390/bacteria3040018.

FAO. 2022. Integrated pest management (IPM): Principles and practices. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Available at https://www.fao.org/pest-and-pesticide-management/ipm/principles-and-practices/en/.

Gebreziher, H.G., Gebreazgaabher, F.G. 2024. Night-time light-traps and push-pull integrated system enhanced the control of different life stages of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). CABI Agriculture and Bioscience 5(104):1-14. doi:10.1186/s43170-024-00307-1.

Guera, O.G.M., Castrejón-Ayala, F., Robledo, N., Jiménez-Pérez, A., Sánchez-Rivera, G., Salazar-Marcial, L., et al. 2021. Effectiveness of push-pull systems to fall armyworm (*Spodoptera frugiperda*) management in maize crops in Morelos, Mexico. Insects 12(4):298. doi:10.3390/insects12040298.

Gunaeni, N., Setiawati, W., Muharam, A., Karjadi, A.K., Murtiningsih, R., Moekasan, T.K., et al. 2024. Intercropping insect repellent plants (irps): a promising strategy for sustainable pest management. Agronomy Research 22(S3):1434-1445. doi:10.15159/AR.24.093.

Hailu, G., Niassy, S., Zeyaur, K.R., Ochatum, N., Subramanian, S. 2018. Maize-legume intercropping and Push-Pull for management of fall armyworm, stemborers, and striga in Uganda. Agronomy Journal 110(6):1-10. doi:10.2134/agronj2018.02.0110.

IPBES. 2023. Summary for policymakers of the thematic assessment report on invasive alien species and their control. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In Roy, H.E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., et al. (eds.) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Secretariat, Bonn, Germany. doi:10.5281/zenodo.7430692.

IPCC. 2022. Climate change 2022: Impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, UK. doi:10.1017/9781009325844.

Jaiswal, D.K., Gawande, S.J., Soumia, P.S., Krishna, R., Vaishnav, A., Ade, A.B. 2022. Biocontrol strategies: An eco-smart tool for integrated pest and disease management. BMC Microbiology 22(1):324. doi:10.1186/s12866-022-02744-2.

Jalloh, A.A., Khamis, F.M., Yusuf, A.A., Subramanian, S., Mutyambai, D.M. 2024. Long-term push-pull cropping system shifts soil and maize-root microbiome diversity, paving way to resilient farming system. BMC Microbiology 24:92. doi:10.1186/s12866-024-03238-z.

Jasrotia, P., Kumari, P., Malik, K., Kashyap, P.L., Kumar, S., Bhardwaj, A.K., et al. 2023. Conservation agriculture-based crop management practices influence insect pest populations and natural enemy dynamics in agroecosystems. Frontiers in Sustainable Food Systems 7:1173048. doi:10.3389/fsufs.2023.1173048.

Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., et al. 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proceedings of the National Academy of Sciences of the United States of America 115(33):7863-7870. doi:10.1073/pnas.1800042115.

Khan, Z.R., Pittchar, J.O., Midega, C.O., Pickett, J.A. 2018. Push-pull farming system controls fall armyworm: Lessons from Africa. Outlooks on Pest Management 29(5):220-224. doi:10.1564/v29_oct_09.

Kremen, C., Merenlender, A.M. 2018. Landscapes that work for biodiversity and people. Science 362:eaau6020. doi:10.1126/science.aau6020.

Lenné, J.M., Wood, D. 2024. Crop diversity in agroecosystems for pest management and food production. Plants 13(8):1164. doi:10.3390/plants13081164.

Luttermoser, T., Khan, Z.R., Midega, C.A.O., Nyagol, D., Jonsson, M., Poveda, K. 2023. Are pests adapting to the push-pull system? Ecologically intensified farms in Kenya maintain successful pest control over time. Agriculture, Ecosystems & Environment 347:108345. doi:10.1016/j.agee.2023.108345.

Mala, M., Baishnab, M., Mollah, M.M.I. 2020. Push-Pull Strategy: An integrated approach to manage insect pests and weed infestation in cereal cropping systems. Journal of Bioscience and Agriculture Research 25(02):2122-2127. doi:10.18801/jbar.250220.259.

Midega, C.A., Pittchar, J.O., Pickett, J.A., Hailu, G.W., Khan, Z.R. 2017. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (JE Smith), in maize in East Africa. Crop Protection 105:10-15. doi:10.1016/j.cropro.2017.11.003.

Munawar, A., Zhu, Z., Machado, R.R., Zhou, W. 2023. Beyond "push-pull": Unraveling the ecological pleiotropy of plant volatile organic compounds for sustainable crop pest management. Crop Health 1:18. doi:10.1007/s44297-023-00018-5.

Murtiningsih, R., Moekasan, T.K., Prabaningrum, L., Gunadi, N., Setiawati, W., Muharam, A., et al. 2024. Light trap-based control threshold: An alternative method for hot pepper pests management. Chilean Journal of Agricultural Research 84:597-605 doi:10.4067/s0718-58392024000500597.

Ndayisaba, P.C., Kuyah, S., Midega, C.a.O., Mwangi, P.N., Khan, Z.R. 2020. Push-pull technology improves maize grain yield and total aboveground biomass in maize-based systems in Western Kenya. Field Crops Research 256:107911. doi:10.1016/j.fcr.2020.107911.

Njeru, N.K., Midega, C.A.O., Muthomi, J.W., Wagacha, J.M., Khan, Z.R. 2020. Impact of push-pull cropping system on pest management and occurrence of ear rots and mycotoxin contamination of maize in western Kenya. Plant Pathology 69(9):1644-1654. doi:10.1111/ppa.13259.

Park, M., Kim, S., Bae, S., Im, M. 2024. Monitoring of pesticide residues in chili peppers using international Pesticide monitoring data for safety management. Toxics 12(7):508 doi:10.3390/toxics12070508.

Qasim, M., Islam, W., Rizwan, M., Hussain, D., Noman, A., Khan, K.A., et al. 2024. Impact of plant monoterpenes on insect pest management and insect-associated microbes. Heliyon 10(20):e39120. doi:10.1016/j.heliyon.2024.e39120.

Rajpoot, P.K., 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. doi:10.33545/26174693.2025.v9.i8a.5070.

Rhainds, M. 2024. Mass trapping lepidopteran pests with light traps, with a focus on tortricid forest pests: What if? Insects 15(4):267. doi:10.3390/insects15040267.

Sánchez-Bayo, F., Wyckhuys, K.A.G. 2019. Worldwide decline of the entomofauna: A review of its drivers. Biological Conservation 232:8-27. doi:10.1016/j.biocon.2019.01.020.

Savary, S., Willocquet, L., Pethybridge, S.J., Esker, P., McRoberts, N., Nelson, A. 2019. The global burden of pathogens and pests on major food crops. Nature Ecology & Evolution 3(3):430-439. doi:10.1038/s41559-018-0793-y.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B: Biological Sciences 375(1794):20190120. doi:10.1098/rstb.2019.0120.

Sileshi, G.W., Kuyah, S., Schuman, M.C., Chidawanyika, F., Muriithi, B.W., Midega, C.O., et al. 2025. Opportunities for expansion of push-pull technology as an agroecological and sustainable intensification approach in Africa. Npj Sustainable Agriculture 3:30. doi:10.1038/s44264-025-00069-x.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., et al. 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Science Advances 6(45):eaba1715. doi:10.1126/sciadv.aba1715.

Wang, Z., Xuan, H., Liu, B., Zhang, H., Zheng, T., Liu, Y., et al. 2025. Diversified cropping modulates microbial communities and greenhouse gas emissions by enhancing soil nutrients. Agronomy 15(6):1472. doi:10.3390/agronomy15061472.

Yang, H., Lu, J., Zhu, P., Sun, Y., Hu, Z., Li, D., et al. 2024. Blue light attracts more *Spodoptera frugiperda* moths and promotes their flight speed. Insects 15(2):129. doi:10.3390/insects15020129.

Yousefi, M., Marja, R., Barmettler, E., Six, J., Dray, A., Ghazoul, J. 2024. The effectiveness of intercropping and agri-environmental schemes on ecosystem service of biological pest control: A meta-analysis. Agronomy for Sustainable Development 44(2):15. doi:10.1007/s13593-024-00947-7.

Zhang, Y., Han, M., Song, M., Tian, J., Song, B., Hu, Y., et al. 2021. Intercropping with aromatic plants increased the soil organic matter content and changed the microbial community in a pear orchard. Frontiers in Microbiology 12:616932. doi:10.3389/fmicb.2021.616932.