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Research Article

Field Evaluation of *Habrobracon hebetor* and *Trichogramma* spp. for Biological Control of Diamondback Moth, *Plutella xylostella*, in Cabbage

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ABSTRACT

Diamondback moth (*Plutella xylostella*) is a major constraint to cabbage production, necessitating effective and environmentally compatible biological control strategies. This study evaluated the efficacy, effects on natural enemies, economic performance, and yield relationships of different biological control treatments against *P. xylostella* in cabbage. All treatments significantly reduced leaf infestation, larval population, and feeding damage compared with the untreated control. Treatment T_7 (*Trichogramma bactrae* + *Habrobracon hebetor*) consistently provided the greatest suppression, reducing leaf infestation to 12.35%, 9.70%, and 3.98% at 14 days after application following the first, second, and third releases, respectively, compared with 59.88%, 64.40%, and 68.17% in the control. T_7 also recorded the lowest mean larval density (0.99 larvae plant^{-1}) and fewest feeding holes (3.62 plant^{-1}), whereas the untreated control had 9.84 larvae plant^{-1} and substantially greater leaf damage. Importantly, parasitoid treatments did not significantly reduce ladybird beetle or spider populations, indicating compatibility with major predatory arthropods. Treatment T_7 also produced the highest marketable yield (87.52 t ha^{-1}), gross return (BDT 1,312,850 ha^{-1}), net return (BDT 1,133,184 ha^{-1}), and benefit–cost ratio (7.3). Regression analysis demonstrated strong associations between yield and healthy leaves (R^2 = 83.51%), larval incidence and infected leaves (R^2 = 73.8%), larval incidence and yield (R^2 = 69.5%), and infected leaves and yield (R^2 = 49.6%). Overall, T_7 effectively suppressed *P. xylostella*, conserved natural-enemy populations, and improved cabbage yield and economic returns. Therefore, T_7 is recommended as an effective, economically viable, and environmentally compatible strategy for managing diamondback moth in cabbage under field conditions.

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Introduction

Cabbage (*Brassica oleracea* var. *capitata*) is an essential cruciferous vegetable cultivated worldwide including Bangladesh as a medicinal plant and food source (Zahid et al., 2024). Its high concentrations of bioactive compounds (glucosinolates, phenolic acids, flavanols, vitamins, and carotenoids) increase its nutritional value in the human diet (Francisco et al., 2017). In Bangladesh, the annual production of cabbage is 217 thousand tons and yields 16.8-tons ha^{-1} which contributes 23.5% of the

total winter vegetable production and ranked fifth among the vegetables produced in Bangladesh (Khan and Talukder, 2017). However, cabbage production faces major constraints because the crop is severely impaired by heavy insect pest infestations, mainly lepidopteran pests (Philips et al., 2014). Among different pests, diamondback moth (DBM), *Plutella xylostella*, is a major insect pest in cabbage under field conditions of Bangladesh (Hasan et al., 2021). It causes damage nearly 15% on leaves and 23.33% to 58.33% on plants, depending on the genotypes (Choyon et al., 2022). This type of damage appears translucent on the leaf. The yield losses due to the infestation of DBM are recorded up to 50% (Akbari et al., 2024). Generally, farmers depend on chemical insecticide to control DBM in cabbage cultivation. Non-judicious use of these chemicals results in environmental pollution, human health problems (Bosch et al., 1982), and secondary effects such as pest resistance, resurgence, and secondary outbreaks (Hill et al., 2017). It is, therefore, a matter of urgency to find sustainable, economical alternatives for pest control. Bio-control agents *Habrobracon hebetor* (Hymenoptera: Braconidae) is a suitable natural larval parasitoid for the control of lepidopteran larvae in the field (Ou et al., 2024). Similarly, *Trichogramma* spp. (Hymenoptera: Trichogrammatidae) wasps, which have a worldwide distribution, have been effectively used in 56 countries over an area of more than 32 million ha for lepidopteran pest suppression (Hassan, 1993) in various crops such as cotton, sugar beet, tomato, and apple (Consoli et al., 2010; Ben Saad et al., 2026). In the context of Bangladesh, cabbage cultivation is seriously affected by DBM, which often leads to yield losses 50% to 80% and farmers mostly rely on chemical-based pesticides in managing DBM (Faruq et al., 2022). However, the indiscriminate use of insecticides promotes the development of insecticide resistance, leading to their resurgence, apart from harming beneficial natural predators, and eventually increasing the production cost (Li et al., 2016).

In contrast, parasitoids such as *H. hebetor* and *Trichogramma* spp. have shown potential pest suppression ranging between 60 and 75% under controlled laboratory conditions and have yet to be explored in the field (Grieshop et al., 2006; El-Wakeil et al., 2013). So, field evaluation is crucial to identify the most effective parasitoid or parasitoid combination for DBM suppression, where environmental factors and interactions among parasitoids can influence their effectiveness. There remain critical knowledge gaps in the interaction effects and impacts on natural enemy populations. This study aims to address this gap through field evaluation to evaluate the field efficacy of *H. hebetor* and *Trichogramma* spp. against diamondback moth in the cabbage and additionally, to determine the combined effect of *H. hebetor* and *Trichogramma* spp. for the management of diamondback moth in cabbage.

Materials and Methods

Experimental site and duration

The study area is located at approximately 22.80°N latitude and 89.50°E longitude. The experiment was conducted in the field conditions at the field laboratory of Agrotechnology Discipline, Khulna University, Khulna, Bangladesh from October 2024 to April 2025.

Experimental design

The study was laid out in a randomized complete block design (RCBD) with 3 replications and 8 treatments, including control. The individual plot size was (2 × 1.5) m^2. Two adjacent unit plots and blocks were separated by 60 cm and 80 cm apart respectively and standard agronomic practices were followed uniformly in all plots.

Treatments

The following biological controls were tested

T_0 = Control

T_1 = *Trichogramma evanescens*

T_2 = *T. chilonis*

T_3 = *T. bactrae*

T_4 = *Habrobracon hebetor*

T_5 = *T. chilonis + H. hebetor*

T_6 = *T. evanescens + H. hebetor*

T_7 = *T. bactrae + H. hebetor*

Field preparation and agronomic practices

The experimental field was initially ploughed using a power tiller, followed by repeated cross-ploughing until the desired soil tilth was achieved. Subsequent laddering and spading ensured proper soil preparation, and residues of previous crops along with uprooted weeds were removed before final levelling. Individual plots (2 × 1.5 m^2) were prepared manually with a spade, followed by the application and incorporation of basal fertilizer into the soil one day prior to transplanting according to the recommended cabbage fertilizer schedule (Barman et al., 2022). Seeds of the cabbage

variety 'ATLAS 75', collected from the Rupsha market, Khulna, Bangladesh, were transplanted in the last week of October at a spacing of 80 cm between rows and 60 cm between plants. The dose used was of urea (300-350 Kg ha^{-1}), TSP (200-250 Kg ha^{-1}), MOP (300-350 Kg ha^{-1}) and cow dung (5-10 tons ha^{-1}). Two to three irrigations were scheduled at 20-30 days intervals of transplanting. Normal cultural operations were common to all experimental condition and DBM was controlled by releasing 4 parasitoids in different combination as designed in the treatment combination without the regular insecticide spray. Data were recorded at 3, 7, 11, and 14 days after application (DAA).

Collection, rearing and releasing techniques of parasitoids

The parasitoids were collected from the Bangladesh Agricultural Research Institute (BARI), Gazipur, and reared in bio-control and IPM laboratory of Khulna University, Bangladesh. *H. hebetor* and *Trichogramma* spp. (*T. chilonis, T. evanescens, T. bactrae*) were released following standard biocontrol protocols. *H. hebetor* was introduced at a rate of 5,000 adults ha^{-1} during early stage of pest infestation, either in the morning or late afternoon, directly onto cabbage leaves with host larvae. For *Trichogramma* spp., parasitized eggs at a rate of 50,000 ha^{-1} were distributed using egg cards (Tang et al., 2017). Releases were repeated at 10-day intervals under high pest pressure.

Yield

The cabbage head was harvested on a different date from the field. After harvesting, healthy cabbage leaves were separated and weighed as per plot (2 × 1.5 m^2). Finally, converted and expressed in tons per hectare.

Economic analysis

The Benefit-Cost Ratio (BCR) was calculated as the sum of costs, the price of producing the crop, and the sum of returns from the specific treatment. In this work, the BCR was estimated on a per-hectare basis. The benefit-cost analysis procedure was organized as follows.

Gross return and total management cost of production

The monetary yield was calculated using the cost accounting method of the gross yield at the unit price of cabbage for that period (BDT. 15/kg). Total management cost of production was calculated by summing all treatment-specific production expenses, including land preparation, seedlings, fertilizers, manure, irrigation, plant protection measures, labor, harvesting, and other relevant inputs.

Net return

Net return was calculated by subtracting the total management cost of production from the gross return.

Net return = Gross return - Total management cost of production

Benefit-cost ratio calculation

The BCR was calculated by using the formula described by Aheeyar et al. (2026) as follows:

$$\text{Benefit cost ratio} = \frac{\text{Gross return}}{\text{Total management cost of production}}$$

Data collection

Data were collected on the total number of leaves $plant^{-1}$, the number of healthy leaves $plant^{-1}$, and the number of infected leaves $plant^{-1}$. In addition, data were taken on head diameter $cabbage^{-1}$, the number of holes $cabbage^{-1}$, and the number of larvae incidence $cabbage^{-1}$. The number of natural enemies, specifically ladybird beetles and spiders, was also recorded.

Statistical analysis

Data were analysed using one-way analysis of variance (ANOVA) in Minitab Statistical Software version 22.3.0. The assumptions of independence, normality of residuals, and homogeneity of variance were checked before analysis. When the ANOVA showed significant differences among treatments, Tukey's Honestly Significant Difference (HSD) test was used for pairwise comparison of treatment means at a 5% significance level ($P < 0.05$).

Results

Effect of treatments on leaf infestation (%)

All treatments significantly reduced leaf infestation compared with the untreated control (Table 1). Throughout all observation intervals at (7, 11 and 14 DAA), treatment T_7 continuously provided the lowest infestation. At 14 days after treatment application, the infestation rates in T_7 dramatically decreased to 12.35%, 9.70%, and 3.98% compared with 59.88%, 64.40% and 68.17% in the control, after the 1st, 2nd, and 3rd releases (Table 1). Treatments T_3, T_1, and T_2 also maintained significantly lower infestation than the control across all releases, with reduction percentages ranging from 64% to 77%. In contrast, T_6 showed the least effectiveness among the treated plots, with relatively higher infestation percentages and lower reduction over control 30% to 50%, indicating limited pest suppression. Across all treatments, infestation levels were lower and reduction percentages higher in the 2nd and 3rd releases than in the 1st.

Effect of treatments on larval population of diamondback moth per Cabbage plant

Compared with the untreated control, all biological control treatments significantly reduced the DBM larval population plant^{-1} (Table 2). Among the treatments, T_7 recorded the lowest grand mean density of 0.99 larvae plant^{-1}, followed by T_4 (2.62 larvae plant^{-1}). In contrast, the untreated control recorded the highest grand mean larval population of 9.84 larvae plant^{-1} (Table 2). The biocontrol treatments also showed significant differences in larval population across the successive releases and assessment dates. At 7, 11, and 14 DAA, the treatments generally maintained lower larval populations than the untreated control. Following the 3rd release, T_1 and T_2 showed statistically similar effects on the number of DBM larvae plant^{-1}, with both treatments recording comparatively higher larval populations than the other biocontrol treatments.

Efficacy of treatments on the number of holes/plants

Table 3 presents the mean number of holes plant^{-1} recorded at 7, 11, and 14 DAA across the 1st, 2nd and 3rd release. All treatments significantly reduced the number of holes plant^{-1} compared with the untreated control (T_0). The untreated control recorded the highest number of holes plant^{-1} throughout the trial, increasing from 7.67 at 7 DAA (1st release) to 15.93 at 14 DAA (3rd release). T_7 recorded the lowest number of holes plant^{-1} at every assessment date, decreasing from 5.33 at 7 DAA (1st release) to 1.63 at 14 DAA (3rd release), for the lowest grand mean (3.62) among all treatments. T_4 (5.28) and T_1 (5.85) showed the next-lowest grand means, followed by T_2 (6.60), T_3 (7.79), and T_5 (8.76). T_6 recorded the highest grand mean among the treated plots (13.27) and, at 14 DAA following the 3rd release, was not significantly different from the untreated control.

Effect of treatments on natural enemies (ladybird beetle)

Data accessible in Table 4 summarizes the information on the population dynamics of ladybird beetles after different treatments were applied. Overall, all the treatments that were released had no significant impact on the population density of ladybird beetle plant^{-1} in contrast to the untreated control. A comparison of the efficacy of different treatments based on the mean number of ladybird plant^{-1} is provided in Table 4. When compared to the untread control treatment, the results of Table 4 showed that none of the parasitoid treatments had any discernible effects. T_7 showed the greatest increase in ladybirds among all the treatments, with an average grand mean of 0.55 ladybird plant^{-1}. T_1 had the second-best efficacy, with an average grand mean of 0.39 ladybird plant^{-1}. The untreated control treatment, on the other hand, had the fewest ladybird plant^{-1} on average (0.25) (Table 4). Furthermore, there was a consistent pattern of efficacy observed in the use of parasitoids up to the 3rd, both at 7, 11 and 14 DAA. However, T_5 and T_6 exhibited statistically equal effect on the number of ladybird plant^{-1} after 3rd release.

Effect of treatments on natural enemies (spider)

Data presented in Table 5 summarizes the population dynamics of spider plant^{-1} following the application of different treatments. Overall, most treatments showed a non-significant effect on spider population density in contrast to the untreated control (T_0). Regarding safety to natural enemies, treatment T_7 maintained the highest grand mean spider density (0.36 spider plant^{-1}), indicating a slight increase in spider density compared to other treatments. Grand means for T_5 (0.29), T_4 and T_6 (0.25 each) showed intermediate effects, while T_2 exhibited the lowest average spider number (0.19).

BCR calculation

Table 6 presents the comparative economic performance of different treatments evaluated for DBM management, based on marketable yield, total production cost, gross return, net return, and BCR. The results showed considerable differences in economic returns among the treatments. Among all the treatments, treatment T_7 showed statistically significant differences for marketable yield, gross return, and net return except for total production cost in cabbage cultivation. The highest marketable yields (87.52 t ha^{-1}), gross returns (BDT 1,312,850 ha^{-1}), net returns (BDT 1,133,184 ha^{-1}) and BCR (7.3) produced in T_7 treated plot in comparison with other treatments and was found to be most profitable for DBM management. The treatments T_3 and T_4 produced marginally higher marketable yield (62.24 and 61.71 t ha^{-1}, respectively) and gross return (BDT 935,576 and 854,016 ha^{-1}, respectively) and net returns (BDT 753,934 and 746,034 ha^{-1}, respectively). Untreated control plot had the lowest yield (17.30 t ha^{-1}) and gross return (BDT 259,500 ha^{-1}). Having applied no treatment inputs, T_0 also had the lowest total cost (BDT 110,233 ha^{-1}) and a positive net return (BDT 149,267 ha^{-1}) and BCR (2.4), though far less than the treated plots. Nonetheless, the gross and marketable cabbage yields of all treatments were economically feasible (BCR >1).

Table 1. Leaf infestation (%) of cabbage plant^{-1} at different releases.

Treatments	Infected leaves plant^{-1} at 7, 11, and 14 DAA																	
	1st Release						2nd Release						3rd Release					
	Infestation (%)			Infestation reduction over control (%)			Infestation (%)			Infestation reduction over control (%)			Infestation (%)			Infestation reduction over control (%)		
	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA
T_0	55.95a	58.98a	59.88a	-	-	-	62.48a	63.57a	64.40a	-	-	-	66.72a	67.24a	68.17a	-	-	-
T_1	20.31b	18.69b	17.66b	63.69	68.31	70.51	17.14b	16.92b	16.30b	72.57	73.38	74.68	16.20bc	16.20bc	16.20bc	75.72	75.91	76.24
T_2	22.75b	19.95b	18.47b	59.34	66.17	69.16	17.84b	17.47b	17.24b	71.44	72.52	73.23	17.06bc	17.06bc	17.06bc	74.43	74.63	74.97
T_3	19.87b	18.98b	18.16b	64.49	67.82	69.67	16.86b	16.33b	15.38b	73.02	74.31	76.11	15.69bc	15.69bc	15.69bc	76.49	76.67	76.99
T_4	25.44ab	24.61ab	24.11b	54.52	58.28	59.74	24.13b	23.85b	23.37b	61.38	73.38	63.71	21.79bc	21.79bc	21.79bc	67.34	67.60	68.04
T_5	26.21ab	23.94b	22.81b	53.16	59.41	61.91	21.75b	21.01b	20.43b	65.19	66.96	68.28	19.83bc	19.83bc	19.83bc	70.28	70.51	70.92
T_6	38.97ab	37.34ab	36.42ab	30.34	36.70	39.19	35.59b	35.15b	34.57b	43.03	44.71	46.32	33.90b	33.90b	33.90b	49.20	49.59	50.28
T_7	14.31b	13.18b	12.35b	74.41	77.65	79.38	11.02b	10.33b	9.70b	82.36	83.76	84.94	6.82c	5.13c	3.98c	89.78	92.37	94.15
F-Value	5.15**	5.16**	7.47**	-	-	-	9.91**	10.94**	11.55**	-	-	-	14.72**	15.39**	16.25**	-	-	-

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae + H. hebetor*. ns = non-significant; ***p*<0.01; **p*<0.05.

Table 2. Effect of treatments on larval population of diamondback moth plant^{-1}.

Treatments	Larval population of diamondback moth plant^{-1}									Grand Mean
	1st Release			2nd Release			3rd Release			
	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	
T_0	8.53±0.64a	8.63±0.46a	9.13±0.23a	10.23±0.06a	10.17±0.29a	10.53±0.49a	8.53±0.64a	11.43±1.10a	11.43±1.10a	9.84
T_1	2.73±0.95b	2.77±0.83b	2.63±0.76b	2.67±1.07bc	2.63±1.01bc	2.60±1.04bc	2.73±0.95b	2.60±1.04bc	2.60±1.04bc	2.66
T_2	2.87±1.16b	2.67±1.07b	2.67±1.07b	2.63±1.01bc	2.60±1.04bc	2.67±0.98bc	2.87±1.16b	2.57±0.90bc	2.57±0.90bc	2.68
T_3	3.07±0.61b	2.70±0.61b	2.73±0.64b	3.03±0.50b	3.03±0.50b	2.97±0.55b	3.07±0.61b	2.90±0.70b	2.90±0.70b	2.96
T_4	2.67±0.50b	2.50±0.56b	2.53±0.55b	2.77±0.64bc	2.77±0.64bc	2.67±0.72bc	2.67±0.50b	2.53±0.75bc	2.53±0.75bc	2.62
T_5	3.07±0.61b	2.70±0.53b	2.80±0.70b	2.63±0.57bc	2.70±0.36bc	2.70±0.40bc	3.07±0.61b	3.00±0.27b	3.00±0.27b	2.85
T_6	2.93±0.70b	2.70±0.61b	2.70±0.52b	3.03±0.75b	3.00±0.85b	3.13±0.61b	2.93±0.70b	3.10±0.66b	3.10±0.66b	2.95
T_7	1.33±0.42b	1.17±0.21b	1.07±0.12b	1.03±0.15c	0.97±0.15c	0.87±0.15c	1.33±0.42b	0.60±0.20c	0.60±0.20c	0.99
F-Value	25.74**	35.42**	43.63**	49.96**	49.61**	55.73**	25.74**	54.38**	54.58**	40.11**

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae + H. hebetor*. ns = non-significant; ***p*<0.01; **p*<0.05.

Table 3. Efficacy of treatments on the number of holes cabbage^{-1}.

Treatments	Hole cabbage^{-1} at 7, 11, and 14 DAA									Grand Mean
	1st Release			2nd Release			3rd Release			
	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	
T_0	7.67±2.08ab	14.43±1.33	14.57±1.46a	14.77±1.31a	14.87±1.31a	15.17±1.36a	15.57±1.29a	15.80±1.14a	15.93±1.17a	14.31
T_1	3.67±0.58ab	6.50±0.60	6.33±0.59ab	6.33±0.71ab	6.23±0.78bc	6.00±0.95bc	5.80±1.04bc	5.80±1.04bc	5.70 ±1.13bc	5.85
T_2	4.73±2.17b	7.47±2.47	7.37±2.57ab	7.20±2.52ab	7.13±2.58abc	6.57±2.21bc	6.33±2.42bc	6.33±2.42bc	6.33±2.42bc	6.60
T_3	6.00±3.95ab	8.30±5.25	8.00±5.10ab	8.03±5.05ab	8.03±5.05abc	7.93±5.05abc	7.97±5.1abc	7.97±5.1abc	7.97±5.1abc	7.79
T_4	3.43±3.16ab	6.07±2.53	5.93±2.59ab	5.77±2.53b	5.53±2.38bc	5.40±2.36bc	5.13±2.42bc	5.13±2.42bc	5.13±2.42bc	5.28
T_5	7.33±3.8bab	9.43±3.79	9.40±3.84ab	9.37±3.56ab	9.00±3.41abc	8.77±3.35abc	8.50±3.3abc	8.50±3.3abc	8.50±3.3abc	8.76
T_6	13.77±5.8ab	14.80±7.19	13.70±6.1ab	12.77±4.45ab	12.80±4.40ab	12.87±4.21ab	12.90±4.2ab	12.90±4.2ab	12.90±4.2ab	13.27
T_7	5.33±3.96a	5.13±1.64	4.63±1.27b	4.30±1.40b	3.83± 0.93c	3.63±0.92c	2.17±1.26c	1.93 ±1.00c	1.63±0.64c	3.62
F-Value	2.67**	2.97**	3.31**	4.11*	4.62*	5.35**	6.41**	6.82**	7.16**	4.82**

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae + H. hebetor*. ns = non-significant; ***p*<0.01; **p*<0.05.

Table 4. Effect of treatments on ladybird plant^{-1}.

Treatments	Ladybird beetle plant^{-1} at 7, 11, and 14 DAA									Grand Mean
	1st Release			2nd Release			3rd Release			
	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	
T_0	0.33±0.23	0.33±0.23	0.27±0.12	0.20±0.00	0.27±0.12	0.20±0.00	0.27±0.12	0.20±0.00	0.20±0.00	0.25
T_1	0.47±0.23	0.47±0.23	0.33±0.23	0.53±0.12	0.47±0.23	0.33±0.12	0.27±0.12	0.20±0.00	0.40±0.20	0.39
T_2	0.20±0.20	0.33±0.23	0.47±0.12	0.33±0.12	0.33±0.12	0.33±0.12	0.27±0.12	0.33±0.12	0.27±0.12	0.32
T_3	0.40±0.20	0.20±0.00	0.47±0.12	0.40±0.00	0.27±0.12	0.47±0.23	0.20±0.00	0.20±0.00	0.20±0.00	0.31
T_4	0.33±0.23	0.47±0.12	0.40±0.00	0.53±0.31	0.20±0.00	0.20±0.00	0.27±0.12	0.20±0.00	0.27±0.12	0.32
T_5	0.40±0.20	0.33±0.12	0.27±0.12	0.27±0.12	0.27±0.12	0.27±0.12	0.33±0.23	0.33±0.12	0.33±0.12	0.36
T_6	0.47±0.23	0.47±0.31	0.47±0.31	0.40±0.20	0.33±0.23	0.27±0.12	0.27±0.12	0.27±0.12	0.27±0.12	0.36
T_7	0.73±0.42	0.53±0.12	0.67±0.42	0.40±0.20	0.87±0.81	0.53±0.42	0.40±0.20	0.33±0.12	0.53±0.31	0.55
F-Value	1.13 NS	0.98 NS	1.12 NS	1.54 NS	1.35 NS	1.24 NS	0.52 NS	1.96 NS	1.62 NS	1.27 NS

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae + H. hebetor*. ns = non-significant; ***p*<0.01; **p*<0.05.

Table 5. Effect of treatments on spider plant^{-1}.

Treatments	Spider plant^{-1} at 7, 11, and 14 DAA									Grand Mean
	1st Release			2nd Release			3rd Release			
	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	7DAA	11DAA	14DAA	
T_0	0.60±0.53	0.27±0.23	0.20±0.00	0.33±0.12	0.40±0.20	0.20±0.20ab	0.27±0.12	0.20±0.00	0.27±0.12	0.30
T_1	0.20±0.20	0.33±0.12	0.33±0.12	0.13±0.12	0.20±0.20	0.07±0.12b	0.27±0.23	0.33±0.12	0.27±0.23	0.24
T_2	0.07±0.12	0.13±0.12	0.13±0.23	0.33±0.12	0.20±0.20	0.13±0.12ab	0.20±0.20	0.20±0.20	0.33±0.12	0.19
T_3	0.07±0.12	0.20±0.00	0.33±0.12	0.40±0.00	0.13±0.12	0.13±0.12ab	0.33±0.12	0.27±0.12	0.33±0.12	0.24
T_4	0.60±0.20	0.60±0.53	0.53±0.23	0.07±0.12	0.07±0.12	0.07±0.12b	0.07±0.12	0.13±0.12	0.07±0.12	0.25
T_5	0.33±0.12	0.33±0.12	0.20±0.00	0.27±0.12	0.33±0.31	0.27±0.12ab	0.13±0.12	0.33±0.12	0.40±0.20	0.29
T_6	0.27±0.12	0.27±0.31	0.13±0.23	0.27±0.23	0.33±0.12	0.13±0.12ab	0.27±0.12	0.27±0.12	0.33±0.23	0.25
T_7	0.53±0.31	0.13±0.12	0.33±0.12	0.27±0.12	0.40±0.20	0.47±0.12a	0.33±0.12	0.40±0.35	0.40±0.20	0.36
F-Value	2.35 NS	1.13 NS	2.20 NS	2.16 NS	1.29 NS	3.14**	1.23 NS	0.81 NS	1.14 NS	1.72

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae* + *H. hebetor*. ns = non-significant; ***p*<0.01; **p*<0.05.

Regression analysis

Regression analysis was performed to evaluate the relationships among pest infestation, plant damage, and cabbage yield under different biological control treatments. The analysis revealed significant relationships among several measured variables, indicating that changes in pest infestation and feeding damage were closely associated with plant performance and yield (Figure 1). The strength and direction of these relationships were assessed using regression equations and coefficients of determination (R^2).

The regression analysis highlights four key relationships (Figure 1). Graph (A) shows a strong positive correlation between yield (t/ha) and healthy per plant, given by healthy leaves = 7.233 + 0.09994 × yield with an R^2 of 83.51%. This indicates that plants with higher yield tended to maintain a greater number of healthy leaves. A positive association was also observed between infected leaves and larval incidence (B), with larval incidence = 1.933 + 0.6877 × infected leaves (R^2 = 73.8%), indicating that greater leaf infection was associated with higher larval incidence. In contrast, larval incidence showed a negative linear association with yield (C). The fitted model, yield = 90.00 -7.534 × larval incidence and R^2 = 69.5% meaning yield drops as larval attack increases. Similarly, infected leaves were negatively associated with yield (D), with the model yield = 80.12 – 5.118 × infected leaves, with an R^2 of 49.6%. Collectively, these relationships indicate that greater pest incidence and leaf damage were associated with reduced cabbage productivity, whereas a greater number of healthy leaves was associated with higher yield. However, these regression relationships represent statistical associations and should not be interpreted as evidence of direct causation.

Discussion

The diamondback moth ranks among the most destructive pests of brassicaceous crops worldwide, causing management costs and yield losses. The rapid development of insecticide resistance in DBM highlights the urgent need for bio-rational tactics that effectively suppress pest populations while safeguarding beneficial predators. The present study demonstrates that augmentative release of parasitoids can substantially suppress pest infestation and improve cabbage productivity. More importantly, the superior performance of T_7 (*Trichogramma bactrae* + *H. hebetor*) compared with the individual parasitoid treatments suggests that targeting different developmental stages of DBM can provide a more comprehensive form of biological control.

Table 6. Comparison of the Benefit Cost Ratio (BCR) under various treatment in managing Diamondback Moth

Treatments	Marketable Yield(t/ha)	Total Cost BDT/ha	Gross Return BDT/ha	Net Return	B: C
T_0	17.30±2.08c	110233b	259500±31244c	149267±18039d	2.4
T_1	56.00±3.11b	179666a	840050±46720b	660384±26974bc	4.7
T_2	56.03±13.36b	179666a	840450±21100b	660784±115661bc	4.7
T_3	62.24±6.92b	179666a	933600±10374b	753934±59900b	5.2
T_4	61.71±7.13b	179666a	925700±10692b	746034±61734b	5.2
T_5	47.16±6.58b	179666a	707350±98734b	527684±57004c	3.9
T_6	47.50±2.79b	179666a	712500±41819b	532834±24144c	4.0
T_7	87.52±7.64a	179666a	1312850±11453a	1133184±66127a	7.3
F-value	23.06**	4.82**	23.06**	23.13***	

T_0 = Neutral T_1 = *T. evanescens* T_2 = *T. chilonis* T_3 = *T. bactrae* T_4 = *H. hebetor* T_5 = *T. chilonis + H. hebetor* T_6 = *T. evanescens + H. hebetor* T_7 = *T. bactrae + H. hebetor*. ns = non-significant; **p<0.01; *p<0.05.

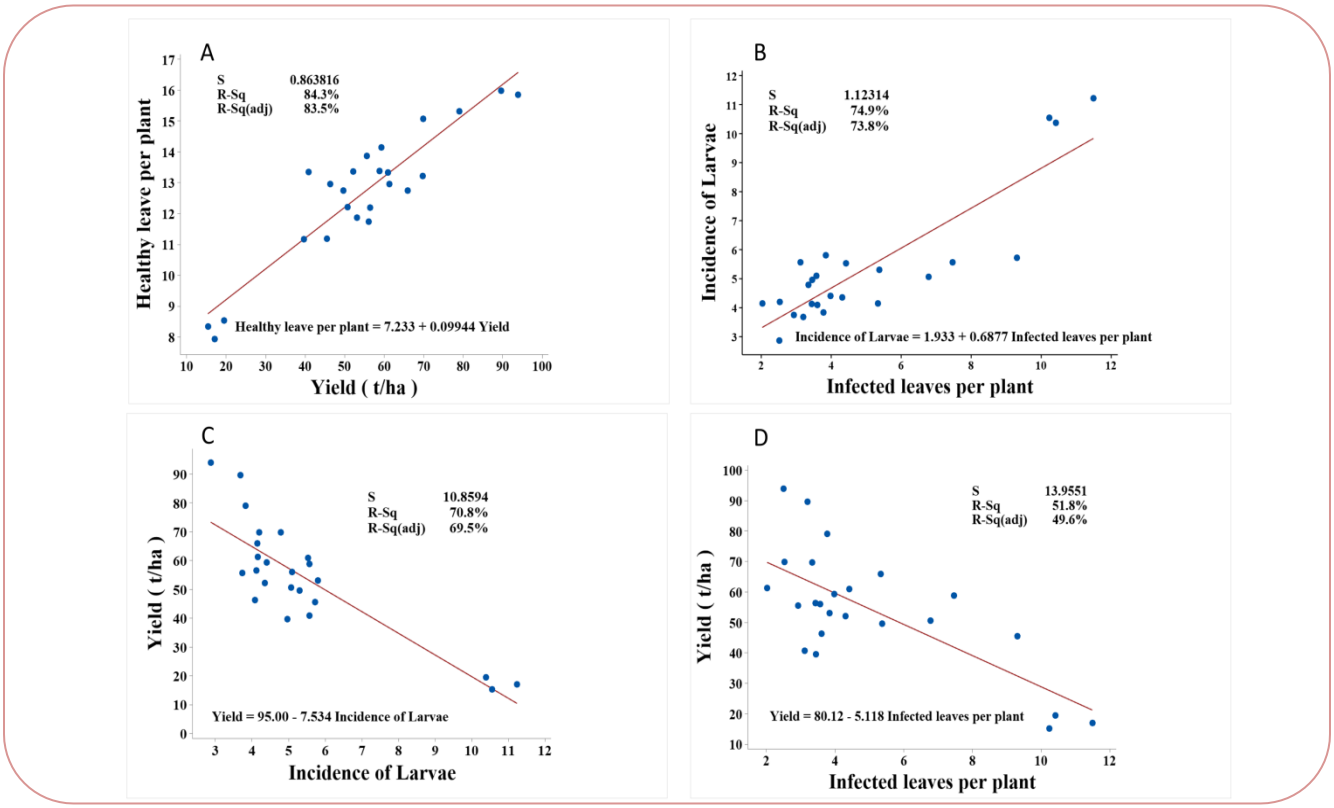


Figure 1. Regression analyses highlighting the impact of yield on healthy leaves per plant (A), infected leaves per plant on incidence of larvae (B), incidence of larvae on yield (C), and infected leaves per plant on yield (D).

Trichogramma spp. primarily parasitizes host eggs, thereby preventing the emergence of larvae, whereas *H. hebetor* is a larval ectoparasitoid that attacks and paralyzes lepidopteran larvae such as DBM. Thus, the combined application potentially acted at two successive stages of pest development, reducing both the number of larvae entering the crop and the survival of larvae that escaped egg parasitism. Such stage-complementary interactions provide a biologically plausible explanation for the superior suppression observed under T_7. The importance of combining natural enemies that attack different host stages has also been demonstrated in other biological-control systems, although the success of such combinations depends on host availability, parasitoid

searching behaviour, release timing, and ecological compatibility. These findings suggest that T_7 was the most efficacious biocontrol treatment for managing DBM under field conditions, resulting in the highest marketable cabbage yield (87.52 t/ha). On the other hand, T_3 (*T. bactrae*–alone) and T_4 (*H. hebetor* alone) produced relatively high yields of 62.24 and 61.71 t/ha, respectively, both were significantly inferior to T_7. This significant decrease in the number of pests is consistent with an earlier study by Ramasamy et al. (2021) and Tang et al. (2017), who stated that *H. hebetor* efficiently control lepidopteran pests by larval parasitization effectively, the synergism between *Trichogramma* spp. and *H. hebetor* likely enhanced parasitism rates, as reported in other investigations (Amr S. Abou El-Ela et al., 2021; Oluwafemi et al., 2009). The success of T_7 might be attributed to the complementary action of the two biological control agents (BCAs), with *Trichogramma* spp. targeting the egg stage and *H. hebetor* attacking the larval stage, thereby disrupting multiple life stages of the pest, as also reported by Zang et al. (2021) and Mbata and Warsi (2019). The present findings are also consistent with field-based research on biological control of DBM in cabbage. Navik et al. (2019) reported that an IPM programme incorporating *T. chilonis* significantly reduced DBM larval populations and cabbage-head damage compared with farmer-practice plots. Their findings demonstrated that parasitoid-based management can reduce feeding injury and improve crop protection under field conditions. In the present study, larval numbers were reflected in decreased levels of damage in cabbage. For example, T_7 had the lowest percentage of infected leaves (3.98% at 14 DAA), whereas T_0 possessed the highest (68%). This implies that effective pest control is necessary not only to reduce direct feeding damage, but also to mitigate secondary effects. Furthermore, the number of holes per cabbage head was statistically reduced in plants treated with T_7, thus confirming the protective action of these BCAs. The capacity of *H. hebetor* and *Trichogramma* spp. to produce healthy plants is important for market yield and reduction of pre- and post-harvest losses. In addition to pest suppression, the investigation also confirmed the positive effects on plant growth and yield parameters after BCAs treatments. The infestation reduction of leaves were significantly higher in T_7 (94.15% at 14 DAA) compared with over control (T_0), indicating that low pest pressure improves photosynthetic efficiency and nutrient partitioning in cabbage plants. This observation supports the study by Uddin et al. (2023) and Eva et al. (2020), who found that pest-free plants allocate relatively more resources to growth and development. Economic considerations also approved the superiority of T_7, which gave a maximum BCR of 7.3 as compared with other treatments, resulting from maximum yield (87.52 t/ha). The untreated control (T_0) produced a significantly lower yield of 17.30 t/ha and had a low BCR of 2.4, further demonstrating the economic benefits of biological control compared with conventional and untreated management methods. These findings are consistent with earlier economic evaluations by Agasyeva (2021) and Cantori et al. (2022), which indicated that BCAs constitute a long-term cost-saving measure by reducing dependence on chemical pesticides and guaranteeing high yields (Fenibo and Tonderayi Matambo, 2025). The high BCR of T_7 indicates that farmers could use it as a sustainable and economical pest management strategy (Singhamuni et al., 2015). Although T_7 was proven to be the most effective treatment, other combinations were still effective. These parasitoids also partially suppressed pest and gave moderate yield (62.24, 61.71 t/ha) as with the treatments T_3 and T_4, wherein alone *T. bactrare* (T_3) and alone *H. hebetor* (T_4) were found close to each other. However, their performance was still inferior to that of T_7, and the combined use of these two BCAs yielded a stronger and more stable action. Notably, the treatments with *T. chilonis + H. hebetor* (T_5) and *T. evanescens + H. hebetor* (T_6) were less effective than the T_7 treatment, probably because the sensitivities and timings of the two parasitoid species released were not compatible (Oatman and Platner, 1971; Cabello et al., 2012). Such variations underscore the need for a suitable choice and effective application of BCAs. The experiment also investigated the effect of BCAs on natural enemy populations, such as ladybirds and spiders. Although they were slightly higher in T_7, the difference was statistically non-significant. This suggests that BCAs do not impact the beneficial arthropod community, contrary to synthetic insecticides, which can have adverse effects on non-target organisms (Klug and Meyhöfer, 2008; Jamshidnia et al., 2018). However, the relatively overall low numbers of spiders in all these treatments could be an indication of a limitation in habitat or sampling bias, and further research is required. Improving habitat for natural enemies (e.g., by providing floral resources or wildflower strips, minimizing the use of broad-spectrum pesticides) can

potentially enhance biological control. Overall, the present findings indicate that the effectiveness of parasitoid-based management of DBM depends not only on the individual performance of a biological-control agent but also on the biological complementarity of the agents used. The superior performance of T_7 might have resulted from simultaneous pressure on different stages of the pest life cycle, with *Trichogramma* targeting eggs and *H. hebetor* targeting larvae. This stage-complementary strategy provides a stronger biological explanation for the observed reduction in pest abundance, feeding damage, and subsequent increase in cabbage yield. The results therefore support further evaluation of T_7 as a component of an IPM program, particularly through multi-season and multi-location experiments that assess parasitoid establishment, parasitism rates, release timing, compatibility with other natural enemies, and economic returns.

Conclusion

This study demonstrates that the combined application of *Trichogramma bactrae* and *Habrobracon hebetor* (T_7) has considerable potential for managing DBM populations in cabbage crops. By targeting complementary life stages, with *T. bactrae* parasitizing eggs and *H. hebetor* attacking larvae, this dual-agent approach resulted in a 92% reduction in larval density compared with the untreated control, along with improved marketable yield and crop quality. The treatments also showed no significant adverse effects on non-target beneficial arthropods, such as ladybird beetles and spiders, indicating their potential with conservation biological control. However, the effectiveness of the treatments varied across observation periods and seasons, suggesting that their performance may be influenced by environmental conditions and pest population dynamics. Therefore, the findings should be interpreted within the scope of the present study, and further multi-season and multi-location field evaluations are needed to validate the consistency and long-term effectiveness of the combined use of *T. bactrae* and *H. hebetor*. Overall, the results suggest that integrating these parasitoids could be a promising component of an environmentally safer integrated pest management strategy for diamondback moth in cabbage.

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Authors' Contributions

MMK and MIH conceptualized the study. MIH conducted the fieldwork, while MMK supervised the project. MMK, MIH, and AM performed the formal analysis. MMK, MIH, AM, EZE, and SD prepared the initial manuscript draft. MMK, SD, AM and MRI contributed in reviewing and editing the manuscript. All authors reviewed and cross-checked the manuscript and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

Policy Addressed

The findings support national IPM policies that prioritize biological control, reduce reliance on synthetic insecticides, conserve beneficial arthropods, and strengthen farmer access to effective parasitoid-based pest-management technologies.

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