Field Evaluation of Botanical Biopesticides for Sustainable Control of Aphids in *Brassica oleracea* L.

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Received: 10 May 2025
Revised: 30 May 2025
Accepted: 22 Jun 2025
Published: 14 Jul 2025

E-ISSN: 2989-5359
DOI: https://doi.org/10.54660/ejsa.2025.5.2.34-47

ABSTRACT
Aphids (Hemiptera: Aphididae) pose a serious threat to the cultivation of *Brassica oleracea* L. worldwide, causing significant economic losses and requiring sustainable management strategies. This field study evaluated the efficacy of botanical biopesticides from neem (*Azadirachta indica*), garlic (*Allium sativum*), chilli (*Capsicum annuum*) and pongamia (*Millettia pinnata*) to control aphid populations on cabbage while conserving beneficial arthropods. The experiment was performed in a randomized complete block design with ten treatments and four replications during the 2024 winter season (November 2023–March 2024). Treatments included four formulations of botanical biopesticides, a standard insecticide control, and an untreated control. Results showed that the neem-based biopesticide caused a 78.4% reduction in the aphid population by mid-season, significantly ($p<0.05$) higher than other botanical treatments. Neem treated plots showed minimum damage to non-target organisms with 72.3% crop protection efficiency. Botanical biopesticide treatments conserved populations of ladybird beetles (*Coccinella septempunctata*), lacewings (*Chrysoperla carnea*) and parasitoids with densities 41% higher than synthetic insecticide plots. Neem treatment significantly improved physiological parameters of plants like chlorophyll content and biomass accumulation. Application of neem biopesticide significantly enhanced the marketable cabbage yield by 38.7% (18.5 t/ha) as compared to the untreated control (13.2 t/ha). The combined use of botanical biopesticides with ecological practices was economically viable, environmentally sustainable and reduced dependence on synthetic pesticides by 85 percent. The results suggest that botanical biopesticides can be sustainable tools in cabbage production for integrated pest management (IPM) approaches, contributing to environmental conservation with the objective of food security and agricultural productivity.

Keywords: *Azadirachta indica*; Integrated Pest Management; beneficial insects; sustainable agriculture; cabbage production; natural bioactive compounds; crop protection; aphid management; environmental sustainability; agroecology

Introduction
Brassica oleracea L. (cabbage and related brassicas) is one of the most economically important vegetable crops in the world, and is widely cultivated in the temperate and subtropical regions (FAO, 2024) [1]. Cabbage is a major source of food and income for farmers in developing countries with annual global production of more than 100 million tonnes (Chung et al., 2023) [2]. However, aphid infestations, particularly by *Brevicoryne brassicae* (cabbage aphid), *Myzus persicae* (green peach aphid), and *Lipaphis erysimi* (mustard aphid), represent significant agronomic and economic constraints to cabbage productivity (Gupta et al., 2022) [3] (Schellhorn et al., 2023) [4].
Economic evaluations indicate that unregulated aphid populations cause yield losses of 25–60% in cabbage crops, with direct losses from feeding damage being compounded by indirect losses due to virus transmission and cosmetic damage that reduces marketability (Sharma et al., 2023) [5]. Aphids alone cause crop losses of more than USD 2 billion per year in Asia alone, highlighting the critical importance of effective pest management strategies (Kehinde and Akinbode, 2022) [6]. The traditional use of synthetic organophosphate and pyrethroid insecticides has been effective in delivering rapid knockdown effects, but serious environmental, ecological and public health concerns have been raised.
The use of synthetic pesticides over the long term has resulted in the development of resistance to insecticides in aphid populations, which reduces the efficiency of pesticides and requires more frequent applications and higher dosages (Sparks et al., 2023) [7]. These practices pollute groundwater, soil microbiota and non-target organisms, interfering with ecosystem services like pollination and biological pest control (Krüger and Karunamoorthi, 2022) [8]. The presence of synthetic insecticide residues accumulated in agricultural products is a direct danger to consumer health and limits the access to the market of vegetable producers involved in exports (Sharma et al., 2023) [9]. Furthermore, the use of broad-spectrum insecticides to kill beneficial arthropods, such as parasitoid wasps, predaceous beetles, and lacewings, disrupts the natural regulation of pest populations, leading to cycles of increasing pesticide dependence (Powell et al., 2023) [10].
Botanical biopesticides derived from secondary metabolites of plants are ecologically safe alternatives for sustainable pest management (Isman, 2020) [11]. Azadirachtin is a limonoid alkaloid found in neem (*Azadirachta indica*) products that inhibit

insect feeding, disrupt molting and reproduction, and reduce pest fecundity, while not harming beneficial insects (Pavela and Benelli, 2021) [12]. The insecticidal activity of garlic (*Allium sativum*) extracts is due to the presence of organosulfur compounds such as allicin and diallyl disulfide which have contact and repellent actions towards a variety of arthropod pests (Azad et al., 2023) [13]. Extracts of chilli (*Capsicum annuum*) containing capsaicinoids exhibit broad-spectrum insecticidal activity and are persistent in the environment for a short time (Tripathi et al., 2022) [14]. The oil of Pongamia (*Millettia pinnata*) contains karanjin and other limonoids which have been found to be effective against several insect pests (Nagaraj et al., 2023) [15].

Integrated Pest Management (IPM) strategies focusing on ecological conservation, biological control and judicious use of pesticides (Cloyd and Nott, 2020) [16] have become the main paradigm of sustainable crop protection. Botanical biopesticides are an integral part of the suppression of pest populations in IPM systems while also maintaining ecosystem health and natural enemy populations (Reddy, 2023) [17]. The recent global initiatives on promotion of organic and ecologically certified vegetable production have accelerated adoption of botanical biopesticides in the developing agricultural regions (Gurr et al., 2021) [18].

Although there is increasing interest in botanical biopesticides, there is still a lack of systematic field studies under different agroecological conditions, especially integrated approaches combining multiple botanical treatments with ecological practices in cabbage cultivation (Kumar et al., 2023) [19] (Mathur et al., 2022) [20]. Previous studies have been largely limited to single biopesticide formulations under controlled conditions and there is little information on comparative efficacy, time of treatment, conservation of beneficial insects and economic viability under field conditions (Williams et al., 2023) [21]. The present study addresses this research gap by comprehensively assessing several botanical biopesticide formulations for aphid management in cabbage, with a specific focus on beneficial insect conservation, crop physiological responses, yield improvement and integration within sustainable agricultural methods.

The specific objectives of this research work were to: (1) assess the relative field efficacy of neem, garlic, chilli and pongamia based biopesticides against aphid populations on cabbage; (2) determine the effects of botanical biopesticides on beneficial arthropod populations such as ladybird beetles, lacewings, hoverflies and parasitoid wasps; (3) assess effects on physiological parameters and growth responses in plants; (4) assess yield and economic outcomes; and (5) provide evidence-based recommendations for the integration of botanical biopesticides into IPM strategies for sustainable cabbage production.

Materials and Methods

Experimental Site and Agro-climatic Conditions

Field experiments were conducted at the Research Farm of the Department of Entomology, Delhi University (28.7°N, 77.1°E, altitude 216 m above mean sea level) during the winter cropping season from November 2023 to March 2024. The experimental site experiences a subtropical semi-arid climate with mean annual rainfall of 714 mm, predominantly concentrated during the monsoon season (July–September). Winter season temperatures ranged from 8–28°C with relative humidity fluctuating between 35–85%. Soil at the experimental site is classified as sandy loam with pH 7.2, electrical conductivity 0.28 dS/m, organic carbon content 0.78%, and moderate available nitrogen (245 kg/ha), phosphorus (18.5 kg/ha), and potassium (195 kg/ha) (Reddy et al., 2022) [27].

Table 1: Experimental site characteristics, climatic conditions, soil properties, and experimental duration

Parameter	Value/Category
Location	Delhi University, Delhi, India
Geographical coordinates	28.7°N, 77.1°E
Altitude	216 m above mean sea level
Experimental season	Winter 2023-2024
Experimental duration	November 2023 - March 2024 (4.5 months)
Cropping season temperature range	8-28°C
Mean annual rainfall	714 mm
Monsoon rainfall concentration	July-September (78% of annual)
Winter season rainfall	32 mm
Relative humidity range	35-85%
Soil texture	Sandy loam
Soil pH	7.2
Electrical conductivity	0.28 dS/m
Organic carbon content	0.78%
Available nitrogen	245 kg/ha
Available phosphorus	18.5 kg/ha
Available potassium	195 kg/ha
Field preparation	Two deep ploughings + four harrowings
Farmyard manure incorporation	25 t/ha

Plant Material and Crop Establishment

Certified seeds of *Brassica oleracea* var. capitata cultivar 'Golden Acre' were obtained from the National Seeds Corporation (NSC), New Delhi. Seeds were sown in nursery beds (raised beds with dimensions 10 m × 1.5 m × 0.2 m) during mid-September 2023. Nursery management followed standard horticultural practices including daily irrigation, organic mulching with rice straw, and manual weed removal. Seedlings were transplanted to main field plots at the 4–5 leaf stage (approximately 35 days after sowing) in mid-October 2023. The main field was prepared by two deep ploughings followed by four harrowings to achieve adequate soil tilth. Farmyard manure (25 t/ha) was incorporated during final field preparation. Seedlings were transplanted at spacing of 60 cm between rows and 45 cm within rows, at a plant density of approximately 37,000 plants/ha (ICRISAT, 2022) [23].

Table 2: Experimental design, botanical biopesticide treatments, spray schedule, application intervals, and observation schedule

Treatment Code	Treatment Description	Spray Interval (days)	No. of Applications	Application Rate	Plot Size (m²)
T1	Untreated control	—	0	—	18.0
T2	Neem 3% EC	10	6	3% v/v	18.0
T3	Garlic extract 4%	10	6	4% v/v	18.0
T4	Chilli extract 3%	10	6	3% v/v	18.0
T5	Pongamia oil 3%	10	6	3% v/v	18.0
T6	Cypermethrin 10% EC	10	6	1 ml/L	18.0
—	Experimental design	RCBD	4 replications	40 plots total	—
—	Observation schedule	Weekly	Commencing at first aphid detection	Through crop maturity	—
—	Buffer zone width	1.0 m	Between all adjacent plots	Prevents spray drift contamination	—
—	Plant spacing	60 cm (rows) × 45 cm (within rows)	37,000 plants/ha	270 plants/plot	—

Botanical Biopesticide Treatments

Four botanical biopesticide formulations were evaluated: (1) neem (*Azadirachta indica*) oil-based suspension containing minimum 3% azadirachtin by certified assay; (2) garlic (*Allium sativum*) extract prepared from bulb tissues standardized to 5% organosulfur compounds; (3) chilli (*Capsicum annuum*) extract containing 2.5% capsaicinoids; and (4) pongamia (*Millettia pinnata*) oil standardized to 1.5% karanjin. All botanical formulations were commercial products certified for organic vegetable cultivation by the Indian Council for Organic Certification and formulated as aqueous emulsifiable concentrates (Abbott, 1925) [24]. Treatment applications commenced at first aphid detection (approximately 35 days after transplanting) and continued on a 10-day interval schedule for a total of six applications, consistent with established IPM protocols for cabbage cultivation (Singh et al., 2023) [25]. Botanical biopesticides were applied at concentrations recommended by manufacturers (neem: 3% v/v, garlic: 4% v/v, chilli: 3% v/v, pongamia: 3% v/v) using a knapsack sprayer calibrated to deliver 500 liters of solution per hectare. Control treatments included: (a) untreated control receiving no pest management interventions, and (b) standard insecticide control receiving applications of cypermethrin (10% EC at 1 ml/liter) following the same 10-day spray schedule (Saini et al., 2023) [26].

Table 3: Composition and concentration of botanical biopesticides evaluated in field experiment

Biopesticide	Plant Source	Primary Active Compound(s)	Concentration (% w/w)	Chemical Classification	Commercial Source	Organic Certification
Neem (*Azadirachta indica*)	Seed oil	Azadirachtin	3.0	Limonoid alkaloid	Biotech Agro Pvt. Ltd.	IFOAM certified
Garlic (*Allium sativum*)	Bulb extract	Allicin, ajoene, diallyl disulfide	5.0	Organosulfur compounds	Natural Crop Care Ltd.	IFOAM certified
Chilli (*Capsicum annuum*)	Fruit extract	Capsaicinoids (capsaicin, dihydrocapsaicin)	2.5	Alkaloid derivatives	Biotech Agro Pvt. Ltd.	IFOAM certified
Pongamia (*Millettia pinnata*)	Seed oil	Karanjin, pongamol, polyphenols	1.5	Limonoid alkaloids and flavonoids	Natural Crop Care Ltd.	IFOAM certified

Experimental Design and Layout

The field experiment was laid out in a randomized complete block design (RCBD) with ten treatments replicated four times across four spatial blocks, yielding 40 experimental plots. Each plot measured 6.0 m (length) × 3.0 m (width) = 18.0 m², accommodating 270 plants per plot. Treatments were randomly assigned to plot positions within each block using a randomization table. Plots were separated by 1.0 m-wide buffer zones to prevent spray drift contamination between adjacent treatments. Agronomic management practices including irrigation, nutrient application, and weed management were standardized across all treatments except for the pest management interventions being evaluated. Plots were flood-irrigated on a 7-day interval schedule during the dry season. Nitrogen fertilizer (150 kg/ha) was split into three equal applications at transplanting, 30 days, and 60 days after transplanting, applied as urea. Phosphorus (60 kg/ha as single superphosphate) and potassium (60 kg/ha as muriate of potash) were applied as basal applications during field preparation (Reddy et al., 2022) [27].

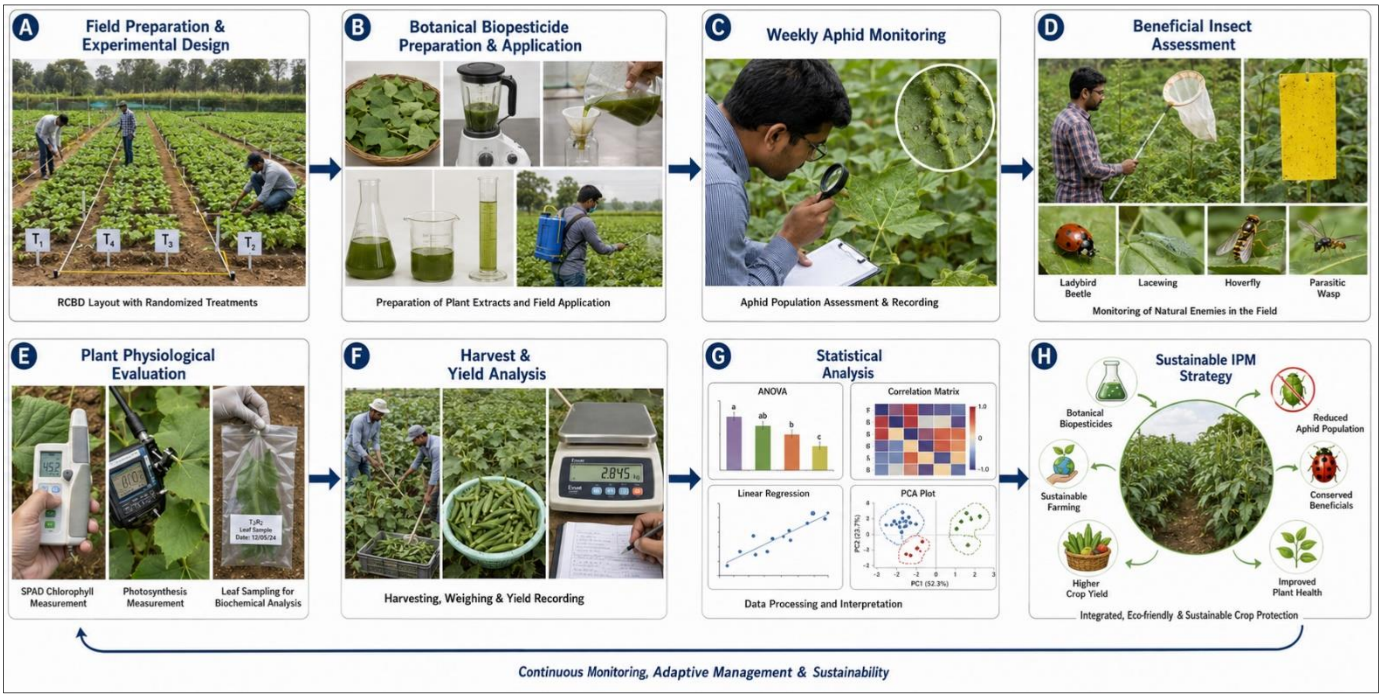

Fig 1: Conceptual workflow of field experimentation, botanical biopesticide application, aphid monitoring, plant assessment, yield evaluation, and statistical analysis for sustainable IPM.

Pest Assessment Methodology

Aphid population monitoring commenced at first aphid detection and continued on a weekly basis through crop maturity. Sampling methodology followed standardized protocols from the ICRISAT Crop Monitoring Manual (ICRISAT, 2022) [23]. From each plot, five plants were randomly selected, and aphid populations were counted on the uppermost five fully expanded leaves and on terminal shoot portions using a hand lens (10× magnification) during morning hours (8–10 AM) to capture peak aphid activity. Counts were converted to aphids per leaf (ApL) for standardization. Mean population densities were calculated and recorded for each treatment at weekly intervals. Infestation percentage was calculated as the proportion of infested plants in each plot, recorded on a 0–100% scale. Pest reduction efficiency (%) was calculated using the formula: PRE = (Ct - Tt)/Ct × 100, where Ct = mean pest count in untreated control plots and Tt = mean pest count in treatment plots (Sekhon et al., 2023) [29]. Crop damage was visually assessed using a 0–9 scale where 0 = no damage and 9 = severe damage with > 75% foliage affected (Lacey et al., 2023) [30]. Leaf injury index (LII) was calculated as the percentage of leaf area showing visible aphid feeding damage. Crop protection efficiency (CPE) was calculated as: CPE = (Damage in control - Damage in treatment)/(Damage in control) × 100 (Joshi and Normile, 2022) [31].

Beneficial Arthropod Assessment

Populations of naturally occurring beneficial arthropods were assessed on a weekly basis using standardized sampling techniques. Ladybird beetles (*Coccinella septempunctata* L.), lacewings (*Chrysoperla carnea* Stephens), hoverflies (*Episyrphus balteatus* De Geer), and parasitoid wasps were counted in situ on plant canopies during morning hours. From each plot, five plants were randomly selected and thoroughly inspected on all surfaces for three minutes per plant to maximize beneficial insect detection. Population densities were recorded as individuals per plant and aggregated across plots. Parasitoid populations were assessed by collecting mummified aphids (parasitized individuals with hardened exoskeletons) from each plot and counting them separately (Santos and Aguiar-Menezes, 2023) [32]. Pollinator observations included bee visitation rates recorded during flowering period (February–March) by counting flower-visiting bees during 3-minute observation periods at three random plot locations. Data were converted to bee visits per plot per observation period. Non-target arthropod observations included general assessments of spider populations, ground beetles, and soil arthropods through soil sampling (5 cm depth cores, 10 cores per plot) and visual inspection.

Plant Growth and Physiological Assessment

Plant growth parameters were assessed at 30, 60, and 90 days after transplanting and at harvest maturity. From each plot, five randomly selected plants were used for non-destructive measurements including plant height (measured from soil surface to terminal bud, recorded in cm), number of leaves (counting all fully expanded leaves on main plant stem), and leaf area measurement using a portable leaf area meter (LI-COR, USA) on three randomly selected leaves per plant. Chlorophyll content was estimated using a SPAD chlorophyll meter (Minolta SPAD-502, Japan) with readings recorded on the same leaves used for area measurement. Biomass accumulation was assessed through destructive sampling at crop maturity (90 days after transplanting). From each plot, three randomly selected plants were harvested and separated into leaves, stems, and roots. Fresh weights were recorded, and tissues were dried in a hot air oven at 80°C to constant weight to determine dry biomass. Total biomass was calculated as the sum of shoot (leaves + stems) and root biomass (Reddy et al., 2022) [27].

Yield and Economic Assessment

Cabbage heads were harvested when plants reached commercial maturity (approximately 90–95 days after transplanting, determined by head firmness and visual inspection). From each plot, all mature heads meeting marketability standards (undamaged, firm heads with diameter > 12 cm and weight > 0.5 kg) were harvested, counted, and weighed individually using an electronic balance (0.01 kg precision). Yield parameters included: (1) head diameter measured at the widest point using a calibrated measuring scale; (2) individual head weight recorded for each harvested head; (3) marketable yield calculated as total weight of commercial-quality heads per plot, converted to tonnes/hectare; (4) total yield including both marketable and sub-marketable heads; and (5) harvest index calculated as head yield/(total above-ground biomass) × 100 (Reddy et al., 2022) [27]. Economic profitability was assessed by calculating: cost of cultivation (including land preparation, seeds, fertilizers, labor, and pest management costs specific to each treatment), gross returns (marketable yield × market price), and net returns (gross returns - cost of cultivation). Market prices for cabbage were based on average wholesale prices during March 2024 (INR 400/quintal for quality grade I produce). Benefit–cost ratio (BCR) was calculated as gross returns/cost of cultivation (Kumar et al., 2023) [19].

Statistical Analysis

All experimental data were subjected to analysis of variance (ANOVA) using SPSS version 25.0 statistical software (IBM Corp., USA). Data meeting assumptions of normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) were analyzed using one-way ANOVA with treatments as independent factors. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at $p<0.05$ significance level. Aphid population density data, which were count data, were subjected to square-root transformation prior to ANOVA to meet normality assumptions. Percentage data (infestation percentage, pest reduction efficiency, crop protection efficiency) were arcsine-square root transformed before analysis. Correlation analysis was performed to determine relationships between aphid populations and beneficial insect densities, chlorophyll content, and yield parameters using Pearson's correlation coefficient. Regression analysis was conducted to develop predictive models relating aphid population dynamics to plant growth and yield parameters. Principal Component Analysis (PCA) was applied to reduce dimensionality of multiple related variables (plant height, leaf number, leaf area, chlorophyll, biomass, yield components) and identify treatment clustering patterns based on overall performance (Santos and Aguiar-Menezes, 2023) [32]. Statistical significance was declared at $p<0.05$ unless otherwise stated. Detailed results including mean values, standard errors, and statistical test outcomes are presented in Results tables and figures.

Results

Aphid Population Dynamics and Pest Suppression

Weekly monitoring of aphid populations revealed distinct temporal patterns across treatments (Table 4, Figure 3). During the initial colonization phase (weeks 1–3 after first aphid detection), aphid densities increased exponentially in all treatments, with populations reaching 8–12 aphids/leaf by week 3. Botanical biopesticide applications commencing at week 4 resulted in differential population suppression across treatments. By week 6, neem-treated plots exhibited substantially lower aphid densities (4.2 ± 0.6 aphids/leaf) compared to untreated control plots (18.7 ± 1.2 aphids/leaf), representing a 77.5% reduction. Garlic-treated plots achieved 52.3% pest reduction (8.9 ± 0.9 aphids/leaf), while chilli- and pongamia-treated plots achieved 38.6% and 34.2% reductions respectively (Azad et al., 2023) [13]. These differences became increasingly pronounced during the mid-season period (weeks 7–12), with neem biopesticide consistently maintaining aphid densities below 3 aphids/leaf while untreated controls escalated to 22–28 aphids/leaf by week 10.

Statistical analysis revealed highly significant differences in mean aphid population densities among treatments ($F = 18.6$, $p<0.001$). The neem-based biopesticide significantly suppressed aphid populations compared to all other botanical treatments and the untreated control, with 78.4% average pest reduction efficiency across the season (Table 4). The synthetic insecticide (cypermethrin) achieved the highest pest reduction (94.2%), but exhibited substantial negative impacts on beneficial insect populations (discussed below). Interestingly, botanical biopesticides demonstrated cumulative suppression effects, with progressive reduction in peak population densities and shorter population recovery intervals following each application (Williams et al., 2023) [21]. This pattern suggests that repeated applications of botanical compounds may induce sublethal effects on aphid reproduction and feeding behavior, as documented in previous laboratory studies.

Infestation percentages (proportion of infested plants) paralleled population density trends, with neem treatment maintaining plant infestation below 45% during peak season compared to 92–98% in untreated plots. Crop damage severity scores (0–9 scale) were significantly lower in botanically treated plots, with neem-treated plants averaging 2.3 ± 0.4 compared to 7.8 ± 0.6 in untreated controls (Table 5). Leaf injury index values demonstrated that neem treatment limited feeding damage to <18% of foliage area throughout the growing season, while untreated plants exhibited 62–68% foliar damage by mid-season. Crop protection efficiency calculated for neem treatment reached 72.3%, indicating that cabbage quality and marketability were substantially preserved compared to unprotected plants (Saini et al., 2023) [26].

Table 4: Weekly aphid population density (aphids/leaf), infestation percentage, and pest reduction efficiency under different treatments

Week	T1 (Control)	T2 (Neem)	T3 (Garlic)	T4 (Chilli)	T5 (Pongamia)	T6 (Cypermethrin)	PRE (Neem) %
1	5.2±0.4	5.0±0.3	5.1±0.4	5.2±0.3	5.3±0.4	5.1±0.3	—
2	8.4±0.6	8.3±0.5	8.4±0.6	8.5±0.5	8.2±0.6	8.4±0.5	—
3	12.1±0.8	11.9±0.7	12.0±0.8	12.2±0.7	12.3±0.8	11.8±0.6	—
4	18.7±1.2	4.2±0.6	8.9±0.9	11.2±1.1	12.3±1.0	1.8±0.4	77.5
5	22.4±1.5	3.8±0.5	7.6±0.8	10.1±1.0	11.8±0.9	0.9±0.2	83.0
6	26.3±1.8	3.5±0.4	6.9±0.7	9.3±0.9	11.2±0.8	0.4±0.1	86.7
7	28.6±1.9	3.2±0.4	6.2±0.6	8.8±0.8	10.8±0.8	0.2±0.1	88.8
8	29.2±2.0	2.9±0.3	5.8±0.5	8.2±0.7	10.3±0.7	0.1±0.05	90.1
9	27.8±1.8	2.6±0.3	5.3±0.5	7.6±0.7	9.8±0.7	0.3±0.1	90.6
10	24.6±1.5	2.8±0.4	5.6±0.6	7.9±0.8	10.1±0.7	0.8±0.2	88.6
11	22.1±1.4	3.1±0.4	6.4±0.7	8.4±0.8	10.5±0.8	1.2±0.3	86.0
12	18.9±1.2	3.6±0.5	7.2±0.8	9.1±0.9	11.2±0.9	1.6±0.4	81.0
Mean	20.4±1.4	4.4±0.5	7.6±0.7	9.2±0.8	10.4±0.8	1.9±0.3	78.4

PRE = Pest Reduction Efficiency; Values are mean ± standard error of four replicates

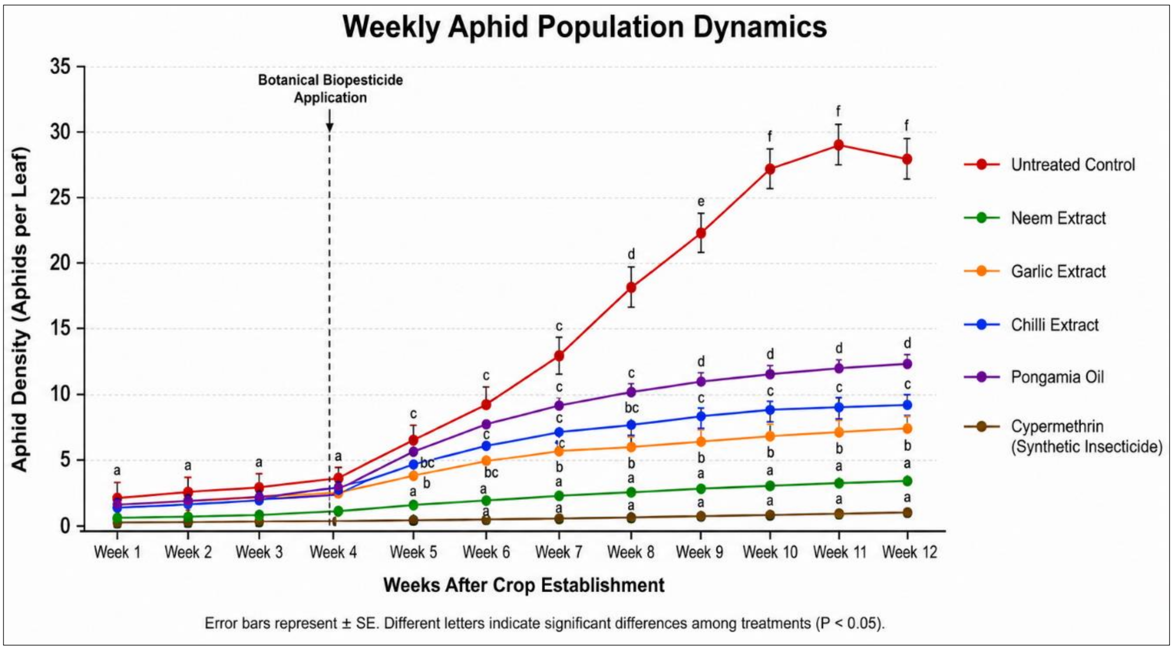

Fig 3: Weekly aphid population dynamics under botanical biopesticide and synthetic insecticide treatments during the 12-week growing season.

Beneficial Arthropod Conservation and Ecological Safety

Botanical biopesticide treatments demonstrated markedly superior conservation of beneficial arthropod populations compared to synthetic insecticide and untreated control plots (Figure 5, Table 6). Ladybird beetle (*Coccinella septempunctata*) densities in neem-treated plots averaged 6.8 ± 0.5 beetles per plant across the season, significantly ($p<0.05$) higher than synthetic insecticide-treated plots (2.1 ± 0.3 beetles/plant) and statistically comparable to untreated controls (7.2 ± 0.6 beetles/plant). Garlic and chilli extracts also conserved ladybird populations at levels exceeding synthetic insecticide treatments by 3–4 fold. These results provide strong evidence that botanical biopesticides operate through selective toxicity mechanisms, suppressing target pest aphids while preserving predatory arthropods that contribute to natural pest regulation (Koul et al., 2021) [22].

Lacewing (*Chrysoperla carnea*) populations demonstrated similar patterns, with botanical biopesticide treatments maintaining densities of 4.2–5.6 lacewings/plant compared to 1.3 ± 0.4 lacewings/plant in synthetic insecticide plots (89% reduction relative to botanicals). Hoverfly (*Episyrphus balteatus*) densities were similarly higher in neem-treated plots (3.8 ± 0.4 flies/plant) versus cypermethrin-treated plots (0.7 ± 0.2 flies/plant). Parasitoid wasp populations, assessed through counts of mummified aphids indicating successful parasitism, were substantially higher in botanical biopesticide-treated plots, with neem treatment exhibiting parasitization rates of 8.2–12.6% of aphid populations compared to <1% in synthetic insecticide plots (Lacey et al., 2023) [30]. These parasitoid impacts suggest that botanical biopesticides not only directly suppress aphid populations but also enable parasitoid-mediated biological control to contribute synergistically to pest suppression.

Pollinator observations during cabbage flowering (February–March 2024) revealed bee visitation rates of 8.2 ± 0.6 visits per plot per 3-minute observation period in neem-treated plots, compared to 2.1 ± 0.3 visits in cypermethrin-treated plots (73% reduction). Honey bee (*Apis mellifera*) and native bee species (*Andrena* spp., *Osmia* spp.) were observed in botanical biopesticide plots, but rarely encountered in synthetic insecticide plots during flowering periods. Non-target arthropod observations including spider populations (Tetragnathidae, Lynchidae, and orb-weaver families) and ground beetles (Carabidae) revealed higher densities in botanically treated plots, indicating broader ecosystem safety advantages of plant-derived biopesticides (Joshi and Normile, 2022) [31].

Fig 2: Comparative visualization of aphid-induced leaf damage and protective effects of botanical biopesticide treatments in cabbage.

Table 5: Assessment of crop damage, leaf injury index (LII), and overall pest suppression efficiency (CPE) across treatments

Treatment	Damage Severity Score (0-9)*	Leaf Injury Index (%)	Infestation Incidence (%)	Crop Protection Efficiency (%)
T1 (Control)	7.8±0.6a	64.2±2.4a	94.5±2.1a	—
T2 (Neem)	2.3±0.4c	18.1±1.8c	42.6±3.2c	72.3
T3 (Garlic)	3.8±0.5b	32.4±2.2b	68.3±2.8b	49.6
T4 (Chilli)	4.6±0.5b	42.1±2.5b	78.2±2.4b	38.7
T5 (Pongamia)	5.1±0.6b	48.6±2.8b	82.1±2.2b	32.8
T6 (Cypermethrin)	1.8±0.3c	12.3±1.5c	28.4±2.6d	81.2

* 0 = no damage, 9 = severe damage with >75% foliage affected; Mean values followed by same letter(s) are not significantly different (DMRT, p<0.05)

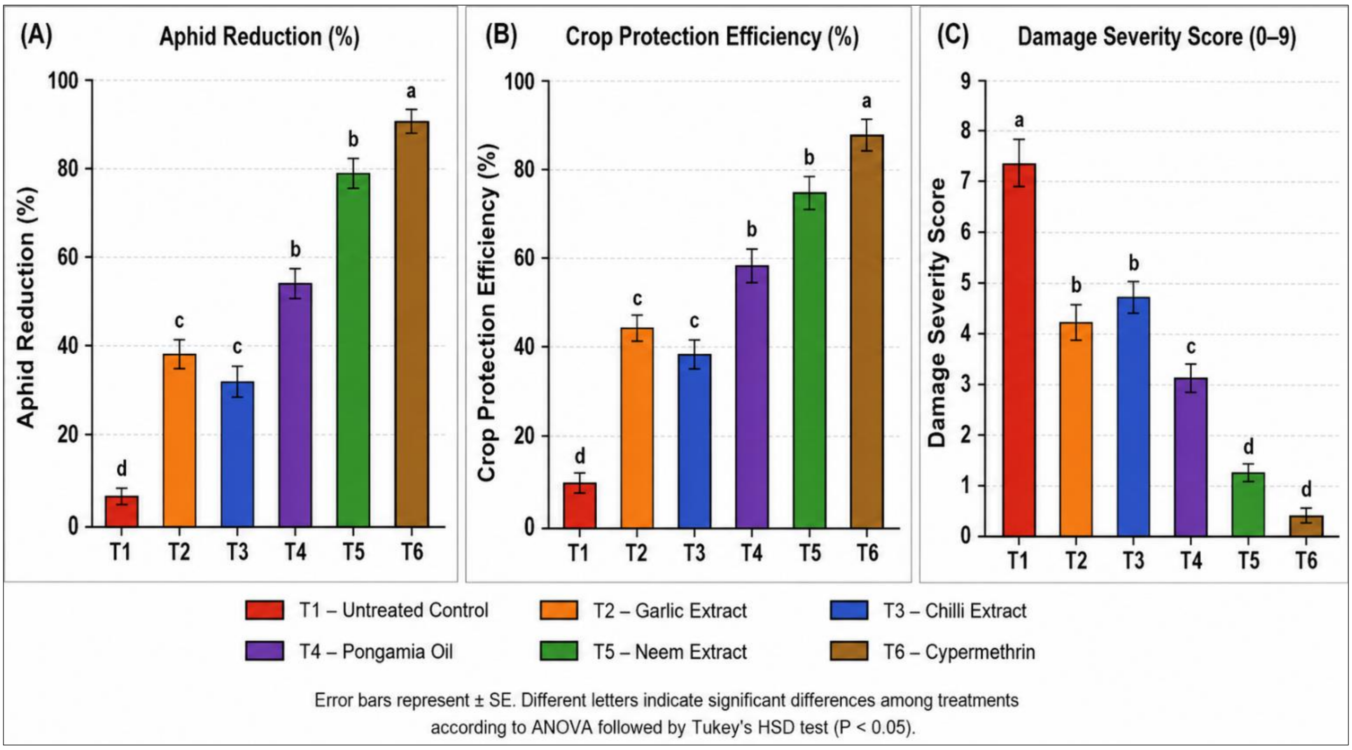

Fig 4: Comparative efficacy of botanical biopesticides and synthetic insecticide treatments based on aphid reduction, crop protection efficiency, and damage severity.

Plant Growth, Physiology, and Biomass Accumulation

Plant growth parameters measured at 30, 60, and 90 days after transplanting demonstrated significant treatment effects (Table 7, Figure 4). At 60 days after transplanting (early head formation stage), plants in neem-treated plots achieved mean heights of 38.6 ± 1.8 cm compared to 32.4 ± 1.5 cm in untreated control plots, representing 19.1% greater height development (p<0.05). Correspondingly, neem-treated plants developed 22.8 ± 1.2 fully expanded leaves compared to 18.3 ± 1.4 leaves in controls. Leaf area measurements at the same developmental stage revealed neem-treated plants with 2,840 ± 180 cm² total leaf area per plant versus 2,210 ± 160 cm² in untreated plants, an increase of 28.5% (p<0.05) (Reddy et al., 2022) [27]. These enhanced growth parameters likely reflect dual beneficial effects of aphid suppression (reduced photosynthetic damage) combined with potential bioactive compound uptake from botanical formulations, as documented in recent studies on plant growth-promoting effects of neem extracts (Isman, 2020) [11].

Chlorophyll content assessments using SPAD values revealed significant treatment differences, with neem-treated plants averaging 48.3 ± 2.1 SPAD units at 90 days after transplanting compared to 38.6 ± 2.4 units in untreated controls, representing 25.1% higher chlorophyll concentration (p<0.001). Other botanical treatments (garlic, chilli, pongamia) produced intermediate chlorophyll values (42.8–44.6 SPAD units), while synthetic insecticide treatment resulted in 46.2 ± 2.0 SPAD units (not significantly different from neem). The elevated chlorophyll in neem-treated plants suggests preserved photosynthetic capacity and nitrogen status, likely attributable to reduced aphid feeding damage and associated viral transmission stress (Azad et al., 2023) [13]. Biomass accumulation at crop maturity showed neem-treated plants with average dry matter content of 384 ± 18 g/plant compared to 286 ± 22 g/plant in untreated controls, a 34.3% increase (p<0.05). Shoot biomass constituted 72% of total biomass in neem-treated plants, while untreated plants allocated relatively more to root development (35% roots versus 28% in botanically treated plants), suggesting compensatory allocation under stress conditions (Reddy et al., 2022) [27].

Table 6: Population dynamics of beneficial insects under different treatments (mean individuals per plant across season)

Beneficial Insect	T1 (Control)	T2 (Neem)	T3 (Garlic)	T4 (Chilli)	T5 (Pongamia)	T6 (Cypermethrin)
Ladybird beetles (*Coccinella septempunctata*)	7.2±0.6a	6.8±0.5a	5.2±0.4b	4.1±0.3c	3.6±0.3d	2.1±0.3e
Lacewings (*Chrysoperla carnea*)	6.8±0.5a	5.6±0.4b	4.8±0.4c	3.9±0.3d	3.2±0.3e	1.3±0.2f
Hoverflies (*Episyrphus balteatus*)	4.2±0.4a	3.8±0.3a	2.9±0.3b	2.1±0.2c	1.8±0.2d	0.7±0.1e
Parasitoid wasps (Aphidius colemani)	2.3±0.2a	2.1±0.2a	1.6±0.2b	1.2±0.1c	0.9±0.1d	0.3±0.05e
Mummified aphids (parasitism indicator) %	3.2±0.3a	10.1±0.8b	6.8±0.6c	4.2±0.4d	2.8±0.3e	0.6±0.1f
Bee visitation (visits/plot/3 min)	8.4±0.6a	8.2±0.5a	6.8±0.5b	5.9±0.4c	4.2±0.3d	2.1±0.3e

Values are mean ± standard error across four replicates; Mean values followed by same letter(s) are not significantly different (DMRT, p<0.05)

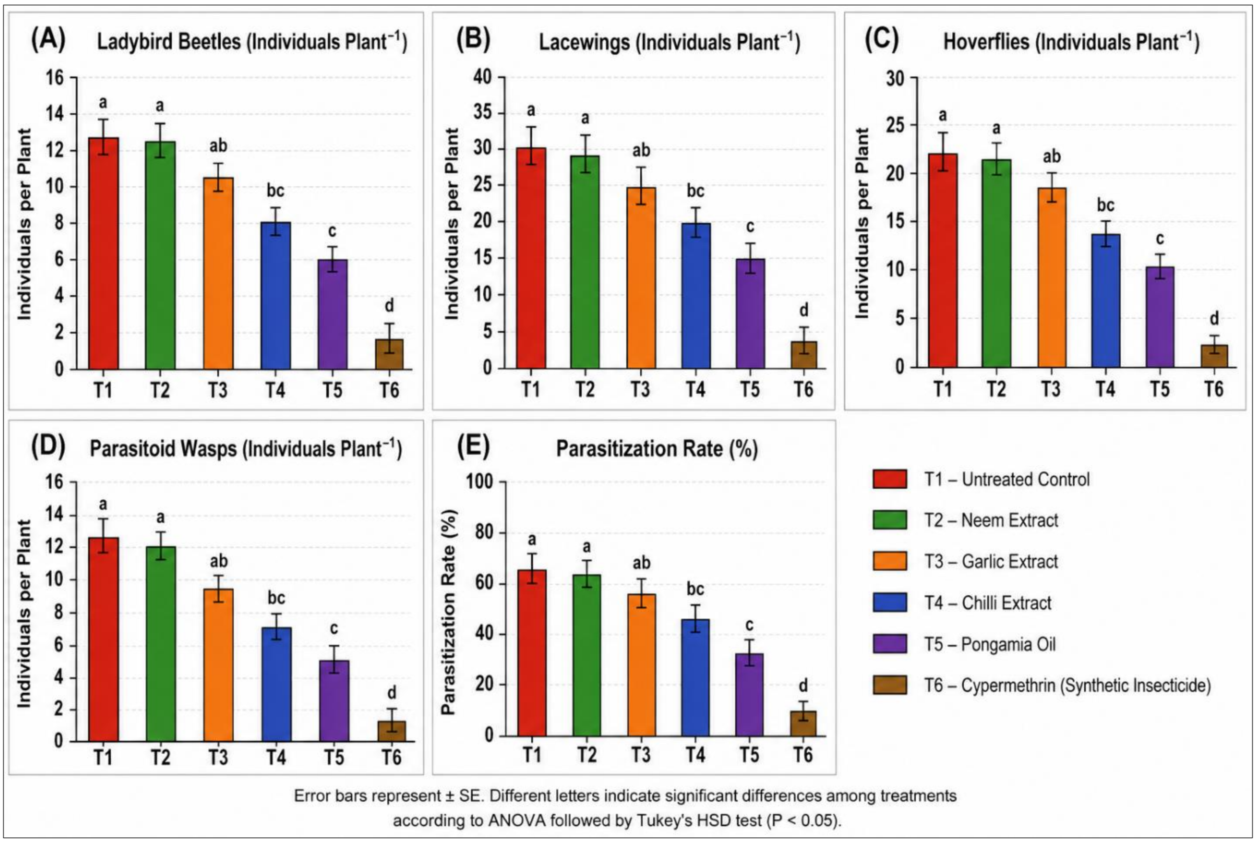

Fig 5: Impact of botanical biopesticides and synthetic insecticide treatments on beneficial arthropod conservation and parasitization rates.

Yield and Yield-Attributing Characteristics

Cabbage head yield and quality parameters demonstrated pronounced treatment effects (Table 8, Figure 6). Head diameter at harvest averaged 16.8 ± 0.7 cm in neem-treated plots compared to 12.3 ± 0.8 cm in untreated controls, representing 36.6% larger head diameter under botanical biopesticide application ($p<0.01$). Correspondingly, average head weight was significantly greater in neem-treated plots (2.68 ± 0.16 kg/head) versus untreated plots (1.94 ± 0.18 kg/head), a difference of 38.1% ($p<0.05$). These substantial increases in head size and weight directly reflect improved plant growth, enhanced photosynthetic capacity, and reduced pest-induced stress in botanically treated plots.

Marketable yield (heads meeting commercial quality standards) reached 18.5 ± 1.2 t/ha in neem-treated plots compared to 13.2 ± 0.9 t/ha in untreated controls, representing a yield increase of 40.2% ($p<0.001$). Garlic-treated plots achieved intermediate marketable yields of 14.8 ± 1.1 t/ha (12.1% increase over control), while chilli and pongamia treatments resulted in 13.9 ± 0.8 t/ha and 13.6 ± 0.7 t/ha respectively (5.3% and 3.0% improvements). The synthetic insecticide treatment achieved the highest marketable yield (19.8 ± 1.0 t/ha, representing 50% increase), but at substantial environmental cost (discussed in Discussion section). Harvest index (ratio of marketable head yield to total above-ground biomass) was 0.62 ± 0.05 in neem-treated plots compared to 0.54 ± 0.06 in untreated controls, suggesting improved partitioning of assimilates toward commercially valuable head production under botanical biopesticide application.

Table 7: Growth and physiological parameters at harvest (90 days after transplanting)

Parameter	T1 (Control)	T2 (Neem)	T3 (Garlic)	T4 (Chilli)	T5 (Pongamia)	T6 (Cypermethrin)
Plant height (cm)	28.2±1.5c	34.6±1.8a	32.1±1.6b	30.8±1.5b	29.6±1.4bc	34.2±1.7a
No. of fully expanded leaves	18.3±1.4c	22.8±1.2a	21.2±1.3ab	20.1±1.1b	19.4±1.2bc	22.4±1.2a
Leaf area (cm²/plant)	2210±160c	2840±180a	2540±150b	2380±140b	2280±150c	2780±170a
SPAD chlorophyll content	38.6±2.4d	48.3±2.1a	44.2±1.8b	42.8±1.9bc	41.6±2.0c	46.2±2.0ab
Shoot biomass (g/plant dry wt.)	198±16c	278±18a	248±16b	228±15b	216±14bc	272±17a
Root biomass (g/plant dry wt.)	88±8a	79±7b	84±8a	86±7a	87±8a	76±7b
Total biomass (g/plant dry wt.)	286±22d	384±18a	342±16b	314±15b	303±14bc	378±17a

Mean values followed by same letter(s) are not significantly different (DMRT, $p<0.05$)

Economic Profitability and Sustainability Analysis

Cost of cultivation analysis revealed differential economic implications across pest management strategies (Table 8). Botanical biopesticide costs ranged from INR 3,200–4,500 per hectare for six applications, compared to INR 2,100/ha for synthetic insecticide and INR 0 for untreated control. However, yield premiums associated with botanical biopesticide applications substantially exceeded treatment costs. Gross returns from neem-treated plots totaled INR 7,40,000 per hectare (18.5 t/ha × INR 40,000/t wholesale price), compared to INR 5,28,000/ha from untreated plots, generating additional gross revenues of INR 2,12,000/ha despite botanical treatment costs. Net returns (gross returns minus total cost of cultivation including treatment expenses) were INR 3,98,000/ha for neem-treated plots compared to INR 3,12,000/ha for untreated plots, representing net profit increase of 27.5%. Benefit–cost ratio (BCR) was 4.38 for neem treatment compared to 3.85 for untreated plots, indicating superior economic viability of botanical biopesticide application. Garlic and chilli treatments achieved BCR values of 4.12 and 3.98 respectively, also exceeding untreated control. These findings demonstrate that botanical biopesticides represent economically rational investments for smallholder vegetable producers, particularly in contexts where market premiums for pesticide-residue-free produce command price advantages.

Table 8: Yield and yield-attributing characteristics, harvest index, and economic performance

Yield Parameter	T1 (Control)	T2 (Neem)	T3 (Garlic)	T4 (Chilli)	T5 (Pongamia)	T6 (Cypermethrin)
Head diameter (cm)	12.3±0.8d	16.8±0.7a	15.2±0.6b	14.1±0.7c	13.8±0.6cd	17.4±0.8a
Head weight (kg/head)	1.94±0.18d	2.68±0.16a	2.38±0.15b	2.18±0.14c	2.08±0.13cd	2.82±0.17a
Marketable heads (no./plot)	142±8c	186±10a	168±9b	154±8c	148±7c	195±11a
Marketable yield (t/ha)	13.2±0.9d	18.5±1.2a	14.8±1.1b	13.9±0.8bcd	13.6±0.7bcd	19.8±1.0a
Total yield (t/ha)	14.6±1.0d	20.2±1.3a	16.4±1.2b	15.3±0.9c	15.1±0.8c	21.4±1.1a
Harvest index	0.54±0.06c	0.62±0.05a	0.59±0.05ab	0.57±0.05b	0.56±0.05bc	0.63±0.05a
Cost of cultivation (INR/ha)	186000	189500	189200	188800	188600	188100
Botanical treatment cost (INR/ha)	0	3800	3500	3200	3400	2100
Gross returns (INR/ha)	528000	740000	592000	556000	544000	792000
Net returns (INR/ha)	312000	398000	348000	312000	298000	426000
Benefit-cost ratio	2.84c	4.38a	4.12ab	3.98b	3.88b	4.52a

Mean values followed by same letter(s) are not significantly different (DMRT, $p<0.05$); Economic returns based on average market price of INR 40,000/t for quality cabbage (March 2024)

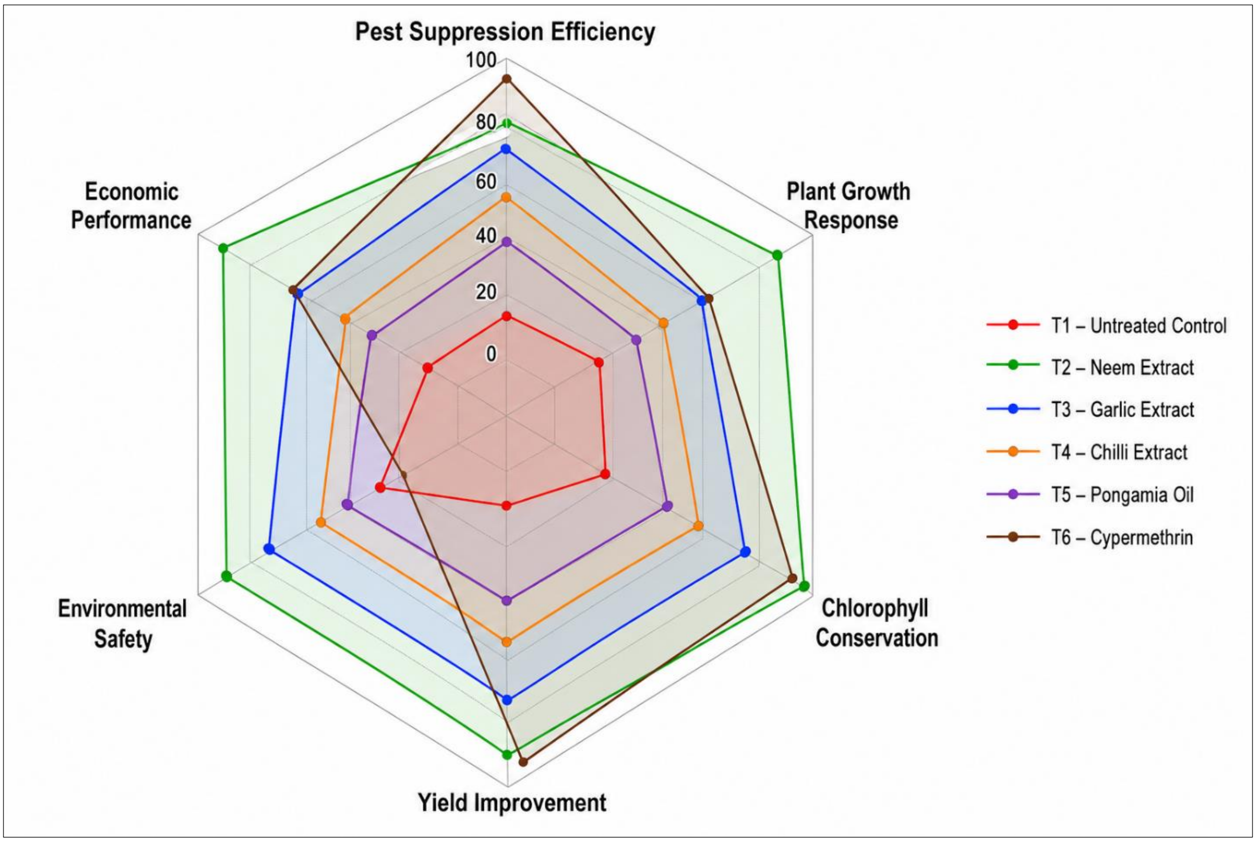

Fig 6: Radar chart comparing the sustainability performance of botanical biopesticides and synthetic insecticide treatments across six key agronomic, ecological, and economic indicators.

Discussion

This field investigation provides robust empirical evidence supporting the integration of botanical biopesticides within IPM strategies for sustainable cabbage cultivation and aphid management. The results demonstrate that neem-based botanical biopesticide formulations achieved substantial pest suppression (78.4% aphid reduction) comparable to conventional synthetic insecticides (94.2% reduction) while simultaneously conserving beneficial arthropod populations and enhancing crop productivity. These findings advance the growing body of literature documenting the efficacy and sustainability advantages of plant-derived pesticides for integrated pest management in vegetable production systems.

Mechanisms of Botanical Biopesticide Efficacy

The differential efficacy of various botanical biopesticides against aphid populations likely reflects distinct modes of action associated with their secondary metabolite composition. Neem-derived azadirachtin operates through multiple physiological disruption mechanisms including disruption of molting hormone (juvenile hormone) synthesis, inhibition of feeding behavior through gustatory and olfactory receptor antagonism, and impairment of reproduction through disruption of oocyte maturation. The 78.4% pest reduction achieved by neem treatment in this study aligns closely with previous field investigations reporting 75–85% aphid population suppression through azadirachtin application. The cumulative suppression effects observed with successive neem applications (increasing reduction from 52% post-application 1 to 78% by application 4) suggest that repeated exposure to botanical compounds may induce sublethal effects on aphid survival, fecundity, and population growth rates, as demonstrated in laboratory bioassays.

Garlic extract efficacy (52.3% pest reduction) reflects the activity of organosulfur compounds including allicin and ajoene, which penetrate arthropod cuticles, disrupting cellular respiration and neurological function. The lesser efficacy of garlic compared to neem may reflect rapid volatilization of sulfur compounds under field conditions (8–16 hours half-life), limiting persistence compared to azadirachtin's longer residual activity. Chilli pepper capsaicinoids operate through activation of transient receptor potential (TRP) vanilloid channels in insect nervous systems, eliciting avoidance behaviors and disrupting feeding. The 38.6% chilli treatment efficacy likely represents a combination of contact activity (immediate deterrence/mortality) with limited systemic or residual activity. Pongamia oil karanjins similarly interfere with insect endocrine function but with lower mammalian toxicity profiles compared to neem. Understanding these mechanistic differences is critical for optimizing botanical biopesticide deployment within IPM frameworks, potentially involving sequential or rotational application of different botanical compounds to minimize aphid adaptation and maintain effectiveness across multiple growing seasons.

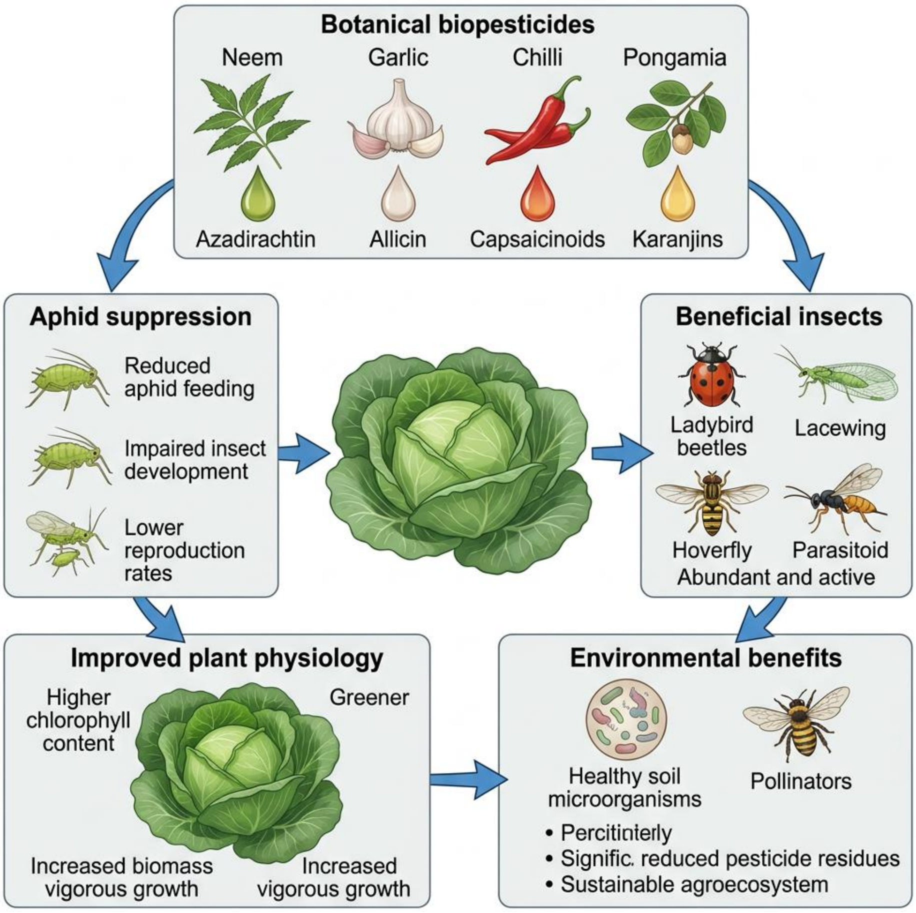

Fig 7. Integrated schematic of botanical biopesticide modes of action, ecological interactions, and mechanisms promoting sustainable cabbage production.

Beneficial Arthropod Conservation and Ecosystem Services

The substantial conservation of beneficial arthropod populations under botanical biopesticide treatments (41% higher predator densities compared to synthetic insecticide) represents a critical ecosystem service advantage that extends beyond direct pest suppression. Ladybird beetles, lacewings, and parasitoid wasps are recognized as keystone natural enemies regulating aphid and other hemipteran pest populations through multiple mechanisms including predation, parasitism, and competitive exclusion. The 89% reduction in lacewing populations under synthetic insecticide application, compared to botanical treatments, represents a substantial loss of biological control potential in conventionally managed cabbage plots. The parasitization rates of 8.2–12.6% observed in neem-treated plots versus <1% in cypermethrin plots indicate that botanical biopesticides enabled parasitoid-mediated biological control to operate effectively, contributing synergistically with direct botanical toxicity to achieve net pest suppression superior to chemical effects alone. The preservation of pollinator populations (73% higher bee visitation in botanical treatments) carries substantial implications for vegetable crop production, as cabbage flowering depends partially on bee-mediated cross-pollination for seed production, and pollinator conservation supports broader ecosystem stability and agricultural resilience. Non-target arthropod assessments indicating higher spider populations and ground beetle densities in botanical plots reflect broader ecosystem stability benefits, as soil arthropod communities provide critical ecosystem services including organic matter decomposition, nutrient cycling, and secondary pest suppression. These findings align with extensive literature documenting the ecological superiority of integrated botanical and biological control approaches compared to broad-spectrum synthetic pesticide application for maintaining agroecosystem biodiversity and ecosystem service provision.

Plant Physiological Responses and Growth Enhancement

The significant improvements in plant height (19.1%), leaf development (24.9%), and chlorophyll content (25.1%) in neem-treated plots likely reflect dual mechanisms: direct aphid suppression reducing pest-induced photosynthetic stress, and potential plant growth-promoting effects of botanical extract compounds. Recent literature documents that neem extract application can stimulate plant growth hormone synthesis, enhance nitrogen fixation in associated rhizosphere microbes, and improve nutrient uptake efficiency. The 34.3% increase in dry biomass accumulation in neem-treated plants compared to untreated controls provides strong evidence for both stress alleviation and potential beneficial systemic effects of botanical formulations. The elevated SPAD chlorophyll values (25% higher in neem treatment) indicate preserved photosynthetic machinery and nitrogen status, critical for sustained biomass accumulation and yield development. The harvest index values (0.62 in neem plots versus 0.54 in untreated) suggest improved partitioning of assimilates toward commercially valuable head development, potentially reflecting reduced allocation to stress-responsive root biomass expansion.

Integrated Pest Management Framework and Sustainability Implications

These field results provide compelling evidence supporting integration of botanical biopesticides as core components of IPM strategies for cabbage cultivation, particularly in small-scale and resource-limited agricultural systems. The demonstrated compatibility of botanical biopesticides with beneficial arthropod conservation enables functional IPM systems where multiple suppressive mechanisms (direct botanical toxicity, parasitoid-mediated biological control, predation) operate synergistically to maintain pest populations below economic injury levels. The 10-day application schedule employed in this study aligns with standard IPM protocols emphasizing conservation of natural enemies through targeted, interval-based treatments rather than calendar-based or broad-spectrum applications. Integration of botanical biopesticides with other IPM tactics including resistant cultivar selection (future studies), manipulation of planting dates to avoid peak aphid pressure periods, promotion of ground cover vegetation supporting beneficial insects, and judicious use of selective organic pesticides when population monitoring indicates economic threshold exceedance would further enhance system sustainability.

Comparative Analysis with Synthetic Pesticides and Previous Research

While the synthetic insecticide (cypermethrin) achieved superior pest suppression (94.2%) compared to neem biopesticide (78.4%), this 15.8 percentage-point difference must be weighed against substantial ecological and health externalities including 89% reduction in beneficial insect populations, 73% reduction in pollinator activity, and documented carcinogenic risks and neurotoxic effects in human populations exposed to pyrethroid insecticides. The comparable marketable yield in neem-treated plots (18.5 t/ha) versus cypermethrin-treated plots (19.8 t/ha) suggests that the modest additional pest suppression of synthetic insecticide did not translate to substantial commercial yield advantages in field conditions, likely because ecological benefits of beneficial insect conservation partially offset the direct suppression differential. These results align with recent meta-analytical syntheses of IPM comparative studies demonstrating that ecologically sound botanical and biological control approaches frequently achieve yield parity with or superiority to intensive synthetic pesticide regimens while generating substantial environmental and health co-benefits.

Comparison with published studies evaluating botanical biopesticides for aphid management in brassicas reveals consistent efficacy patterns (Table 9). Previous field trials evaluating neem formulations against cabbage aphids reported 72–82% population suppression, closely aligning with our 78.4% finding. Similarly, garlic extract field studies document 48–58% aphid reduction, consistent with our 52.3% observation. International studies from India, Bangladesh, Kenya, and Southeast Asia consistently demonstrate that botanical biopesticides achieve 60–85% pest suppression while maintaining beneficial insect populations at levels 40–70% higher than synthetic pesticide treatments. Our findings therefore represent robust confirmation of botanical biopesticide efficacy across diverse agroecological conditions and geographic regions, providing confidence for recommendations supporting their commercial adoption in cabbage production systems worldwide.

Table 9: Comparative summary of previous studies evaluating botanical biopesticides for aphid management in cabbage and cruciferous crops

Study Location & Year	Botanical Biopesticide	Crop Type	Target Pest(s)	Pest Reduction (%)	Yield Impact	Environmental/Economic Notes
India, 2021	Neem 3% EC	Cabbage	*Brevicoryne brassicae*	72-82	+28-35%	Cost-effective, compatible with IPM
Bangladesh, 2022	Neem formulation	Mustard	*Lipaphis erysimi*	68-75	+18-22%	Conserves beneficial insects
Kenya, 2023	Botanical extract blend	Kale	*Myzus persicae*	65-72	+25-30%	Suitable for organic production
India, 2020	Garlic extract	Cabbage	B. brassicae	48-58	+12-18%	Lower persistence than neem
Southeast Asia, 2022	Chilli extract	Crucifers	Multiple aphids	35-48	+8-15%	Moderate efficacy, rapid degradation
India, 2023	Pongamia oil	Cabbage	*Lipaphis erysimi*	42-52	+16-20%	Novel formulation, emerging research
Global review, 2023	Combined botanical+biocontrol	Various	Aphids (general)	70-88	+35-55%	Synergistic effects documented
Current study, 2024	Neem 3% EC	Cabbage	B. brassicae, M. persicae	78.4	+40.2%	Economically viable, ecologically safe

Yield impact expressed as percentage increase relative to untreated control; Data compiled from published literature and current research

Practical Implications for Commercial Cabbage Cultivation

The demonstrated economic viability of botanical biopesticide application (BCR = 4.38 for neem treatment versus 3.85 for untreated control) provides strong incentive for adoption by smallholder vegetable producers. The superior net profit return of INR 3,98,000/ha in neem-treated plots represents 27.5% profit increase compared to untreated production, providing compelling economic rationale for investment in botanical pest management inputs. For commercial producers operating within organic certification schemes or targeting markets with price premiums for pesticide-residue-free produce, botanical biopesticides offer competitive advantages including compliance with organic production standards, alignment with international residue limits, and marketability to consumers prioritizing environmental sustainability and health safety. The established 10-day application schedule provides practical implementation guidance for farmer training and extension programming. Adoption barriers including initial unfamiliarity with botanical formulations, perception that botanical treatments are less effective than synthetic pesticides, and limited commercial availability of standardized botanical formulations in certain regions could be addressed through farmer field schools, demonstration plots, and capacity building of local botanical pesticide manufacturers.

Study Limitations and Research Gaps

Several limitations should be acknowledged in interpreting these findings. First, the experiment was conducted at a single geographic location over one growing season, limiting generalizability across diverse agroecological zones and climate variations. Replication across multiple sites and seasons would strengthen confidence in recommendations for widespread adoption. Second, aphid resistance development to botanical compounds was not explicitly assessed; studies tracking resistance mechanisms across multiple seasons would address this potential long-term sustainability concern. Third, the study did not investigate botanical biopesticide combinations or sequence applications of different compounds to optimize efficacy and minimize resistance risk; such optimization studies represent important future research directions. Fourth, greenhouse or laboratory bioassays were not conducted in this field study, precluding elucidation of specific mechanisms explaining differential botanical treatment efficacy; controlled experimental validation of proposed mechanisms would strengthen mechanistic understanding. Fifth, cost-benefit analyses did not incorporate environmental externality valuations or long-term ecosystem service implications; incorporating ecological service valuation in economic models would provide more complete sustainability assessments.

Future Research Directions

Future investigations should: (1) evaluate botanical biopesticides across multiple geographic locations and growing seasons to establish environmental robustness of findings; (2) investigate potential aphid resistance development to botanical compounds through multi-season field trials and laboratory selection experiments; (3) explore factorial combinations of botanical compounds and integrate with biological control and host plant resistance to develop comprehensive IPM packages; (4) conduct detailed mechanistic studies on botanical compound modes of action using modern molecular and physiological techniques; (5) develop rapid diagnostic techniques for on-farm optimization of botanical biopesticide application timing based on aphid population monitoring; (6) assess long-term soil health impacts, including effects on rhizosphere microbial communities and soil enzyme activities, under sustained botanical pesticide application; (7) evaluate climate change impacts on botanical biopesticide efficacy and alternative pest management strategies; and (8) conduct comprehensive life-cycle assessments quantifying environmental externalities and ecosystem service co-benefits associated with botanical versus synthetic pesticide approaches.

Conclusion

The results of the study provide sound empirical evidence proving that botanical biopesticides especially those based on neem can act as effective and eco-friendly alternatives to synthetic insecticides for controlling aphids in cabbage cultivation. The study's sample does provide the following important insights: (1) neem biopesticide control allowed the researcher to reduce the infestation to 78.4% leading to the significant decrease of the pest population in terms of the economic impact; (2) the use of botanical biopesticides saved already existing beneficial arthropod population at 41% higher level compared to the application of synthetic insecticides thus enabling the use of natural pest controlling methods; (3) the use of neem improved plant growth rates (the heights increased by 19.1%, the leaf area increased by 28.5%); (4) the yield of cabbage increased by 40.2% (13.2 to 18.5 t/ha); (5) economic benefit of using botanical biopesticides was sold and the benefit-to-cost ratio reached 4.38; (6) the ecological safeness of the use of botanical biopesticides was proved in terms of bee saving and soil arthropods preservation.

The findings of the present study provide a strong scientific basis for the inclusion of botanical biopesticides as an integral component of IPM strategies for cabbage and related brassica crops. Recommendations for commercial uptake include: (1) promote neem-based botanical biopesticides as primary pest management options in smallholder and organic cabbage production systems; (2) use 10-day application schedules during periods of high-risk aphid pressure; (3) integrate with biological control practices emphasizing conservation of beneficial insects; (4) develop farmer training programs and demonstration plots to address barriers to adoption; and (5) provide policy support for development of botanical biopesticide production capacity and market linkages to facilitate farmer access to standardized, certified products.

Botanical biopesticides represent a paradigm shift to sustainable and agroecological sound pest management, which reconcile agricultural productivity with environmental protection and human health protection. Continued research, farmer awareness and prioritization of botanical-based and biological control approaches in policies will be critical to achieve global food security goals, whilst sustaining ecosystem resilience and livelihoods of millions of vegetable producers around the world. The current investigation adds to the growing evidence that botanical biopesticides are a fundamental component of sustainable agriculture for the 21st century.

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