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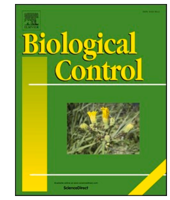

Wheat intercropping with canola promotes biological control of aphids by enhancing enemy diversity

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HIGHLIGHTS

- Wheat intercropped with canola reduces aphid numbers through enhanced natural enemies' abundance.
- Natural enemy abundance increased with canola, supporting the "enemy hypothesis."
- Niche differentiation and predator synergy in diverse systems improved pest suppression through top-down control.
- Diversified cropping systems improved pest suppression through niche complementarity.
- Organic fields with diverse crops showed stronger biological control than conventional fields.

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ABSTRACT

Intensive agriculture relies largely on monocultures and plant protection chemicals to sustain food security but leaning towards such practices undermines environmental sustainability due to negative impacts towards ecosystem services. This increases the need of biodiversity driven pest management strategies especially for wheat, one of the main food crops, worldwide. In Pakistan, which is comprised in area origin of wheat, we evaluated the biological control potential of canola-wheat strip cropping and alternate row intercropping compared to wheat sole cropping against wheat aphids in crop seasons of 2021 and 2023 in organic and conventional fields. Abundance, evenness and diversity of aphids and natural enemies were lower and higher, respectively, in alternate-row intercropping compared to wheat monocrop in both conventional and organic farm types. Contrarily, pest richness was similar among cropping systems in both farming types in 2023, but natural enemies' richness was greater in intercropped plots in both the years. Natural enemies' density and diversity indices proved to be strong predictors of aphid suppression in the fields. Increased enemies and reduced aphids in the diversified systems show positive complementarity among the enemies having different hunting behaviours and suggest the acquisition of floral and prey resources provided by canola. Our study has implications for the management of wheat aphids in its area of origin through ecological intensification at a pilot scale for steering agricultural systems toward agroecological redesign.

1. Introduction

Challenges to meet food requirements for humans have steered cropping practices towards agricultural intensification and monoculture practices which accentuate arthropod pest problems in agroecosystems (Gagic et al., 2021; Meehan et al., 2011). To address the challenges frequent applications of pesticides became the first choice (Deguine et al., 2021; Hossard et al., 2017), whose overly dependence resulted in biodiversity losses (Geertsema et al., 2016; Wan et al., 2018a) and reductions in key ecosystem services such as pollination (Deguines et al., 2014) and biological control of crop pests (Geiger et al., 2010; Zhao et al., 2015). Lack of biocontrol agents escalated losses due to pest outbreaks (Dainese et al., 2019). To reverse this trend, ecological intensification is proposed (Pywell et al., 2015; Tittonell, 2014). It aims enabling the efficient use of available resources to promote ecosystem services towards reducing pest pressure and harms of pesticides without

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sacrificing yields (Rodrigues et al., 2018; Ullah et al., 2020). Ecological intensification can be achieved through the management of non-crop habitats, but also crop diversification (Wan et al., 2018a; Westphal et al., 2015). It invites to move away from straightforward control methods targeting individual pests, towards developing ecological networks involving insect pests, their natural enemies, and various crop diversification plans (Hatt & Döring, 2024). The focus lies in averting pest pressure by strengthening regulations at the agroecosystem level (Wyckhuys et al., 2022). It involves integrating pest management efforts with farming practices sustaining soil productivity and crop health while safeguarding food security and economic viability (Hatt & Döring, 2023).

Wheat, *Triticum aestivum* L. (Poaceae) is an important food grain and a staple food for 35 % of the world's population (Mahmood et al., 2024). Originating from Middle East / West Asia, it is one of the most cultivated cereal crops in temperate climate regions (Albahri et al., 2023). Aphids (Hemiptera: Aphididae) are the most destructive pests of wheat with the ability to inflict 30 % losses through direct feeding and via transmission of pathogens (Wang et al., 2022). As the world population is soaring at an unprecedented rate and is bound to cross the 10 billion mark by 2050 (Raza et al., 2024), there is an ever-increasing demand for an increase in wheat yield to feed the increasing population. This renders aphid management in wheat very critical. Although cultural practices and resistant cultivars can help wheat tolerate moderate aphid injuries (Aradottir and Crespo-Herrera, 2021), insecticide application is still the primary measure to control greater damage by wheat aphids in emergencies. In this context, it is crucial to implement pest management strategies that do not rely on insecticides for wheat aphids and at the same time are resilient and economically viable for farmers (Huss et al., 2022).

Diversifying wheat by intercropping canola (*Brassica napus* L., Brassicaceae) plants in different patterns can serve the purpose. Intercropping consists of growing at least two different crop species together at least for a time. Intercropping can increase cropping system productivity by enhancing land-use efficiency (Li et al., 2020) and can strengthen farm resilience by stabilizing yield (Döring & Elsalahy, 2022; Raseduzzaman & Jensen, 2017) against insect pests. Intercropping can reduce their primary infestation (Döring, 2014) and spread (Mansion-Vaquié et al., 2020) and favour their natural enemies (Rakotomalala et al., 2023). According to Chaplin-Kramer et al. (2011), natural enemy diversity can increase up to 50 % in heterogeneous cropping systems in comparison to simpler ones. With increased natural enemy diversity, biological control can increase by up to 36 % in general, and aphid control by up to 33 % (Chaplin-Kramer et al., 2011; Iverson et al., 2014; Redlich et al., 2018).

Beyond crop diversification, introducing heterogeneity through flowering habitat can provide multiple resources to natural enemies through alternate foraging (alternative prey, pollen and nectar), resting sites, and pesticide-free areas (Gurr et al., 2016). Flower provisioning is expected to attract natural enemies, and enhance their life cycle, egg-laying capacity and finally their biocontrol efficacy (Hatt & Osawa, 2019). This is in accordance with the resource complementation/supplementation process of Tilman (1982) (Dunning et al., 1992). It suggests that heterogenous cropping systems through the introduction of flowering species increase resource availability to natural enemies which increases their density and richness. Such increase in the natural enemies promotes and sustains ecosystem services provided by them. Additionally, a higher richness of natural enemies can directly promote pest control (Dainese et al., 2019; Zhao et al., 2015). Increased enemy richness facilitates their complementarity through niche differentiation based on varying resource usage patterns (temporal and spatial differences in prey consumption) and behaviours (different prey preferences) (Straub et al., 2008). It leads to reducing enemy-free space but also competition for resources, which tend to increase pest suppression (Alhadidi et al., 2018; Gontijo et al., 2015).

We hypothesized that increasing plant species richness by associating a flowering crop with a cereal can provide pest suppression by supporting natural enemies. Two patterns of wheat-canola intercropping were compared to wheat sole cropping for their effects on the abundance, richness, evenness and diversity of pests and their natural enemies.

2. Material and methods

2.1. Experiment site

The field experiment was conducted during the winter seasons (November to March) 2021 in conventional fields, and 2023 in both conventional and organic fields, at the Entomology Research Area, Bahauddin Zakariya University, Multan, Pakistan (30°25′70.5″ N, 71°51′22.1″ E). The Multan region has an elevation of 216.41 m above the mean sea level (Mahar et al., 2024). The climate of the area is a hot desert with sub-tropical to semi-arid conditions so classified as BWh (Köppen-Geiger Climate Classification scheme) with a yearly mean temperature of 25.6 °C (Geiger, 1961; Ismail et al., 2024). The region experiences scorching and extended summers with temperatures reaching up to 52 °C, while winters can reach temperatures as low as −1°C and the average annual rainfall is approximately 186 mm (Hussain et al., 2024). Soil is silt clay and alkaline in nature in this area. The locality is important in terms of productions of wheat, cotton and vegetable crops. In the research area, conventional field routinely receives synthetic fertilizers, whereas organic farming areas have not received any synthetic fertilizer or pesticide since its establishment in 2003. The organic fertility in the organic farming area is maintained through the periodic application of organic manure from livestock farms. No insecticides were sprayed at any stage of the plant growth during this study.

2.2. Experimental design

The experiment involved two crops i.e. wheat, *Triticum aestivum* L. (cultivar: Akbar) and canola, *Brassica napus* L. (cultivar: Super Raya). The experiment was laid out on the conventional and organic farming fields in a randomized complete block design with three cropping systems i.e. wheat sole crop, strip crop and alternate row intercrop referred as treatments and three replications (blocks). Each treatment was 4 m long and 2 m wide. Bare soil buffer zones of one and two-meters width were maintained between treatments and blocks (Fig. 1a). A fine seed bed was prepared at the time of sowing by ploughing and rotavating the soil. The seeds of both crops were sown by single row hand drill on the 16th of November for both years at a seed rate of 125 kg/ha for wheat and 7.5 kg/ha for canola. Planting density was 200 plants/m^2 and 100 plants/m^2 for wheat and canola, respectively. Row spacing in wheat sole crop and alternate row intercrop treatment was maintained at 0.25 and 0.45 m, respectively. In the strip crop treatment, two rows of canola were planted on the border with a 0.45 m distance from adjacent wheat rows on both sides while maintaining a 0.25 m distance between wheat rows (Fig. 1b).

2.3. Insect monitoring

Insect monitoring started from the third week of January as insect populations were negligible prior to this week and sampling continued until the crops reached maturity (end of March). Monitoring comprised six events every year. Aphids were counted weekly by randomly selecting 18 wheat plants from six rows of each treatment plot by avoiding two rows on the border. Selected plants were visually examined gently from stem and leaves in the beginning (tillering and heading stages) and from ears in the later stages (flowering, milking and maturity stages) (Ahmed et al., 2022; Aslam et al., 2005). On the same whole plant, larvae of hoverflies (Diptera: Syrphidae) and lacewings (Neuroptera: Chrysopidae), both larvae and adults of ladybird beetles

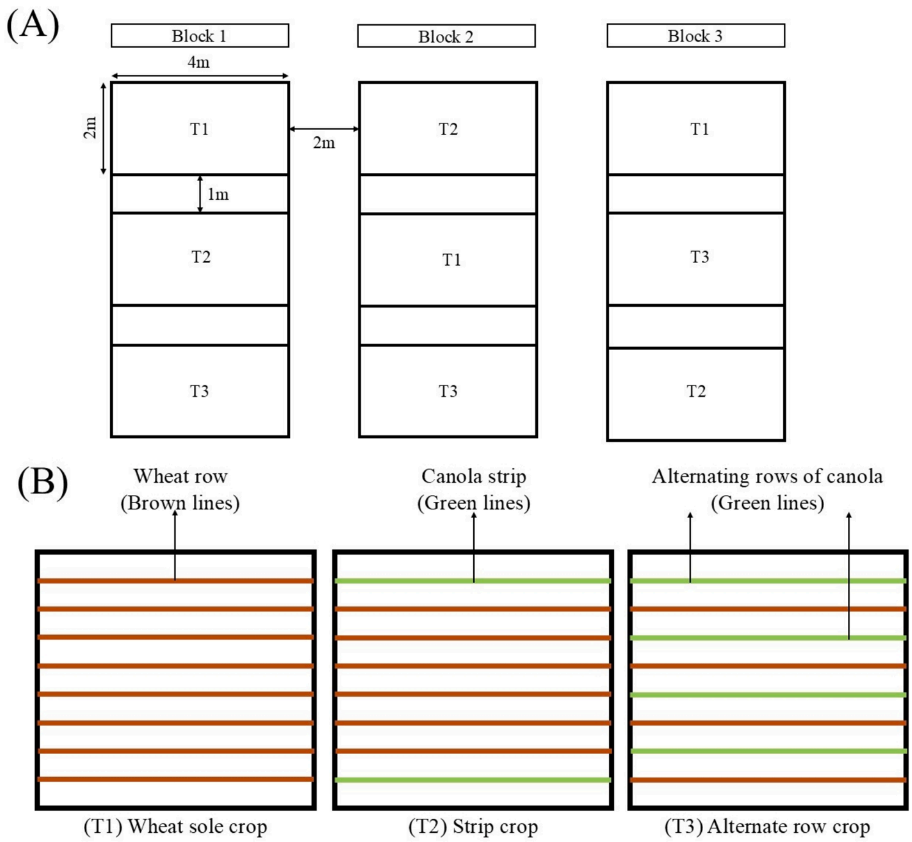

Fig. 1. Configuration of treatments and crop rows within treatments in the experimental design.

(Coleoptera: Coccinellidae), adults of pentatomid bugs (Hemiptera: Pentatomidae) and parasitoids (Hymenoptera: Aphelinidae and Braconidae) were counted through visual inspection by gently observing the plant and samples including parasitoids were also taken to the laboratory for identification up to family level (Bacci et al., 2006). While inspecting plants, ladybird beetles that drop on the ground were also counted from ground area of plant canopy (Shah et al., 2017). Insect monitoring was performed before noon. Aphids, ladybird beetles and green lacewings were identified up to species level while all other natural enemies were identified up to the family level. Voucher specimens were deposited in the IPM laboratory of the Department of Entomology.

2.4. Statistical analysis

Abundances of the different aphid species (pests) i.e., *Sitobion avenae* (F.), *Schizaphis graminum* (Rondani) and *Rhopalosiphum padi* (L.) and different natural enemy families i.e., syrphids, coccinellids, chrysopids, pentatomids, braconids and aphelinids were pooled across all sampling dates for each cropping system in 2021 (under conventional farming) and 2023 (under both organic and conventional farming) (Table 1). For pests and natural enemies separately, Margalef richness index, evenness (calculated by the formula of Simpson diversity i.e. 1-D (Smith and Wilson, 1996), where D is Simpson dominance) and Shannon-Wiener diversity index were calculated using PAST (Palaeontological Statistics) software version 4.13.

To assess the effect of cropping systems and farm type on calculated indices in 2021 (conventional farming) and 2023 (conventional and organic farming averaged), we employed a generalized linear mixed model (GLMM) by taking cropping system and farm type as fixed factor and plots (i.e. replications) as random factor using Gaussian

Table 1
Total counts of pests and natural enemies observed in 2021 and 2023.

Hexapods	Conventional 2021 Wheat sole crop	Strip crop	Alternate row intercrop	2023 Wheat sole crop	Strip crop	Alternate row intercrop	Organic 2023 Wheat sole crop	Strip crop	Alternate row intercrop
Pests									
Sitobion avenae	4808	900	762	3826	908	374	1903	3112	2629
Schizaphis graminum	5186	5666	4113	3512	4357	3794	1844	287	177
Rhopalosiphum padi	30	4	0	34	6	2	20	2	0
Natural enemies									
Syrphidae	29	154	287	17	76	204	61	245	258
Coccinellidae	317	435	569	32	147	385	71	212	332
Braconidae	0	4	7	0	1	3	0	12	27
Aphelinidae	0	4	9	0	0	0	0	1	2
Pentatomidae (predatory)	0	0	0	1	1	12	11	163	403
Chrysopidae	37	71	98	0	0	0	0	0	0

distribution. Analyses were conducted for both years separately because significant effect of year on pest and natural abundances was observed (Table S1). For 2023 specifically, GLMM with Gaussian distribution were also used to study the effects on the calculated indices of cropping systems, farm types (organic vs. conventional) and their interaction as fixed factors and including plots as a random factor. We calculated the effective degree of freedom by Satterthwaite approximation, and significant differences among the diversity indices for fixed factors were evaluated using the Least Significant Difference (LSD) test. Finally, we performed simple linear regression to find the relationship between pest abundance and four predicators, i.e. natural enemies' abundance, richness, evenness and diversity separately for 2021 and 2023. GLMM was run using IBM SPSS, version 21, and regression graphs were plotted using GraphPad Prism Version 9 (GraphPad Inc., San Diego, California, USA).

3. Results

Across the two study years and farming systems, the most abundant aphid species were *S. graminum* and *S. avenae*. The most abundant natural enemies were ladybird beetles (adults and larvae of *C. septempunctata* and *C. undecimpunctata*) and hoverflies (larvae). Pentatomid bugs were especially abundant in diversified organic farming, and lacewings (larvae) were observed in 2021 only (Table 1).

3.1. Effect of cropping systems on pests and natural enemies in 2021 and 2023

Aphid abundance was significantly lower in alternate-row intercropping, whereas wheat sole cropping exhibited the highest aphid abundance in both years (2021: $F_{3,6} = 74.445$, P=<0.001; 2023: $F_{2,10} = 24.729$, P=<0.001) (Tables 2 and 3). Conversely, the highest abundance of natural enemies was observed in alternate-row intercropping, and wheat sole cropping had the lowest natural enemies' abundance in both years (2021: $F_{3,6} = 1835.38$, $P < 0.001$; 2023: $F_{2,12} = 197.104$, $P < 0.001$) (Tables 2 and 3). Alternate-row intercropping and strip cropping had significantly lower pest richness (2021: $F_{3,6} = 148.795$, $P < 0.001$; 2023: $F_{2,12} = 4.194$, $P = 0.042$), evenness (2021: $F_{3,6} = 289.398$, $P < 0.001$; 2023: $F_{2,12} = 44.031$, $P < 0.001$) and diversity (2021: $F_{3,6} = 153.408$, $P < 0.001$; 2023: $F_{2,12} = 38.674$, P < 0.001) (Tables 2 and 3). On the contrary, these treatments had significantly higher natural enemies' richness (2021: $F_{3,6} = 40.060$, $P < 0.001$; 2023: $F_{2,12} = 3.922$, P $= 0.049$), evenness (2021: $F_{3,5} = 86.276$, $P < 0.001$; 2023: $F_{2,12} = 37.780$, $P < 0.001$) and diversity (2021: $F_{3,4} = 163.555$, $P = 0.006$; 2023: $F_{2,12} = 16.481$, P < 0.001) than wheat sole cropping (Tables 2 and 3).

3.2. Effect of cropping systems and farm types on pests and natural enemies in 2023

Both in organic and conventional farming, alternate-row intercropping and strip cropping had significantly lower pest abundance ($F_{1,10} = 7.803$, $P = 0.009$), pest evenness ($F_{2,12} = 5.084$, $P = 0.025$) and pest diversity ($F_{2,12} = 38.674$, P $P < 0.001$) and significantly higher natural enemy abundance ($F_{2,12} = 15.769$, $P < 0.001$), richness ($F_{2,12} = 4.406$, $P = 0.037$), evenness ($F_{2,12} = 8.694$, $P = 0.005$) and diversity ($F_{2,12} = 5.180$, $P = 0.024$) than wheat sole cropping (Table 4). Across cropping systems, organic fields had significantly lower pest abundance ($F_{1,10} = 88.033$, $P < 0.001$), pest evenness ($F_{1,12} = 6.449$, $P = 0.026$) and pest diversity ($F_{1,12} = 5.694$, $P = 0.034$) than conventional fields (Table 5). On the contrary, organic fields had significantly greater natural enemies' abundance ($F_{1,12} = 59.689$, $P < 0.001$), richness ($F_{1,12} = 18.427$, $P = 0.001$), evenness ($F_{1,12} = 293.609$, $P < 0.001$) and diversity ($F_{1,12} = 105.803$, $P < 0.001$) than conventional ones (Table 5).

Table 2
Abundance, richness, evenness and diversity (Means ± SE) of overall insects, pests and natural enemies comparing the cropping systems in 2021.

Variables		Wheat sole crop	Strip crop	Alternate-row intercrop
All insects				
	Abundance	3496.471 ± 345.98a	2394.138 ± 304.23b	1932.264 ± 290.18c
	Margalef richness index	0.62 ± 0.02a	0.73 ± 0.03b	0.79 ± 0.03b
	Evenness	0.53 ± 0.02a	0.37 ± 0.01b	0.48 ± 0.02a
	Shannon-Wiener diversity index	0.85 ± 0.03a	0.76 ± 0.03a	0.97 ± 0.03b
Pests				
	Abundance	3365.506 ± 326.48a	2168.813 ± 274.67b	1608.725 ± 255.92c
	Margalef richness index	0.247 ± 0.03a	0.173 ± 0.02b	0.135 ± 0.02b
	Evenness	0.5 ± 0.02a	0.237 ± 0.02b	0.262 ± 0.02b
	Shannon-Wiener diversity index	0.709 ± 0.03a	0.403 ± 0.02b	0.43 ± 0.02b
Natural enemies				
	Abundance	127.26 ± 31.06a	222.67 ± 31.06b	323 ± 31.06c
	Margalef richness index	0.45 ± 0.04a	0.62 ± 0.05b	0.69 ± 0.05b
	Evenness	0.34 ± 0.02a	0.51 ± 0.03b	0.56 ± 0.03b
	Shannon-Wiener diversity index	0.63 ± 0.04a	0.91 ± 0.05b	0.98 ± 0.05b

The generalized mixed effect model generated means. Different alphabets show significant differences in row-wise comparisons adjusted using the Least significant difference (LSD) test at a 5% level of significance.

3.3. Effect of natural enemies' density and diversity on pest suppression

In 2021, natural enemies' density ($F_{1,7} = 40.32$; $P < 0.001$; Fig. 2a), richness ($F_{1,7} = 49.89$; $P < 0.001$; Fig. 2b), evenness ($F_{1,7} = 17.68$; $P = 0.004$; Fig. 2c) and diversity ($F_{1,17}$22.14; $P = 0.002$; Fig. 2d) were significantly and negatively associated with overall pest abundance. Similarly, also in 2023, natural enemies' density ($F_{1,16} = 20.45$; $P < 0.001$; Fig. 3a), richness ($F_{1,16} = 27.81$; $P < 0.001$; Fig. 3b), evenness ($F_{1,16} = 43.81$; $P < 0.001$; Fig. 3c) and diversity ($F_{1,16} = 62.11$; $P < 0.001$; Fig. 3d) were significantly and negatively associated with overall pest abundance.

4. Discussion

4.1. Crop diversity for biological control

Wheat is vulnerable to aphids which result in economic losses (Shah et al., 2017; Shahzad et al., 2013). We hypothesized that added plant species into wheat could reduce their density, possibly through enhancing biological control by natural enemies, in contrast to wheat crops grown alone. To test this, we compared wheat sole cropping with two diversified cropping systems, i.e. by planting canola rows within the wheat crop (alternate-row intercropping) or strips outside the wheat crop as a border on two sides (strip cropping). We demonstrate that these two diversified cropping patterns can allow for the control of pests as density and diversity were lower for aphids and higher for their natural enemies in these systems. It is consistent with numerous

Table 3
Abundance, richness, evenness and diversity (Means ± SE) of overall insects, pests and natural enemies comparing cropping systems in 2023 (conventional and organic farming averaged).

Variables		Wheat sole crop	Strip crop	Alternate-row intercrop
All insects				
	Abundance	1795.84 ± 95.09a	1567.5 ± 85.96b	1419.79 ± 81.96b
	Margalef richness index	0.6 ± 0.04a	0.65 ± 0.04a	0.73 ± 0.04b
	Evenness	0.52 ± 0.02a	0.37 ± 0.02b	0.42 ± 0.02b
	Shannon-Wiener diversity index	0.82 ± 0.03a	0.77 ± 0.04a	0.93 ± 0.03b
Pests				
	Abundance	1755.45 ± 100.74a	1407.79 ± 86.47b	1133.53 ± 77.37c
	Margalef richness index	0.27 ± 0.05a	0.2 ± 0.04b	0.17 ± 0.03b
	Evenness	0.5 ± 0.04a	0.23 ± 0.03b	0.17 ± 0.03b
	Shannon-Wiener diversity index	0.72 ± 0.03a	0.39 ± 0.03b	0.3 ± 0.04b
Natural enemies				
	Abundance	33.55 ± 7.04a	128.5 ± 15.67b	261.53 ± 30.44c
	Margalef richness index	0.4 ± 0.11a	0.52 ± 0.07b	0.6 ± 0.05b
	Evenness	0.49 ± 0.02a	0.6 ± 0.01b	0.6 ± 0.01b
	Shannon-Wiener diversity index	0.77 ± 0.04a	0.98 ± 0.04b	1.02 ± 0.04b

The generalized mixed effect model generated means. Different alphabets show significant differences in row-wise comparisons adjusted using the Least significant difference (LSD) test at a 5% level of significance.

previous studies showing that wheat-based intercropping systems are generally less infested by pests as reviewed by Lopes et al. (2016). Our findings support the "resource concentration" hypothesis, which suggests that herbivores are more likely to locate and dominate on plants that are growing in pure stands; and that the most niche-specific species regularly reach higher relative densities in simplified field environments (Root, 1973). Indeed, we observed a higher pest evenness, richness and diversity of aphids in wheat sole cropping compared to strip cropping and alternate-row intercropping.

Canola, as a flowering plant, may foster biological control agents. Flowering habitats in field crops increase the populations of natural enemies (Hatt et al., 2017). This can be explained by the "natural enemy

Table 5
Abundance, richness, evenness and diversity (Means ± SE) of overall insects, pests and natural enemies comparing organic and conventional farm types in 2023.

Variables		Conventional	Organic
All insects			
	Abundance	1931.66 ± 87.53a	1303.77 ± 69.81b
	Margalef richness index	0.57 ± 0.03a	0.76 ± 0.04b
	Evenness	0.39 ± 0.01a	0.47 ± 0.02b
	Shannon-Wiener diversity index	0.71 ± 0.03a	0.95 ± 0.02b
Pests			
	Abundance	1814.87 ± 95.05a	1094.94 ± 67.75b
	Margalef richness index	0.22 ± 0.04a	0.2 ± 0.03a
	Evenness	0.32 ± 0.03a	0.23 ± 0.02b
	Shannon-Wiener diversity index	0.49 ± 0.03a	0.38 ± 0.03b
Natural enemies			
	Abundance	65.34 ± 10.62a	165.78 ± 20.09b
	Margalef richness index	0.38 ± 0.20a	0.61 ± 0.04b
	Evenness	0.44 ± 0.02a	0.64 ± 0.01b
	Shannon-Wiener diversity index	0.66 ± 0.05a	1.1 ± 0.03b

The generalized mixed effect model generated means. Different alphabets show significant differences in row-wise comparisons adjusted using Least significant difference (LSD) test at 5% level of significance.

Table 4
Abundance, richness, evenness and diversity (Means ± SE) of overall insects, pests and natural enemies comparing interactions between farm types and cropping systems in 2023.

Variables	Conventional Wheat sole crop	Strip crop	Alternate-row intercrop	Organic Wheat sole crop	Strip crop	Alternate-row intercrop
All insects						
Abundance	2479.58 ± 126.33a	1834.73 ± 111.29b	1584.33 ± 106.24c	1300.64 ± 101.17a	1339.19 ± 101.81a	1272.33 ± 100.70a
Margalef richness index	0.55 ± 0.05a	0.53 ± 0.06a	0.63 ± 0.06b	0.65 ± 0.05a	0.79 ± 0.06b	0.84 ± 0.06b
Evenness	0.51 ± 0.03a	0.34 ± 0.03b	0.35 ± 0.03b	0.54 ± 0.03a	0.39 ± 0.03b	0.5 ± 0.03a
Shannon-Wiener diversity index	0.76 ± 0.04a	0.63 ± 0.05b	0.73 ± 0.05a	0.88 ± 0.04a	0.87 ± 0.04a	1.07 ± 0.04b
Pests						
Abundance	2461.57 ± 136.40a	1758.71 ± 112.02b	1380.8 ± 100.63c	1451.89 ± 97.12a	1126.89 ± 93.94b	930.53 ± 89.45c
Margalef richness index	0.26 ± 0.05a	0.2 ± 0.04a	0.2 ± 0.04a	0.27 ± 0.06a	0.21 ± 0.05a	0.15 ± 0.04a
Evenness	0.5 ± 0.04a	0.33 ± 0.04b	0.19 ± 0.03b	0.5 ± 0.04a	0.16 ± 0.03b	0.15 ± 0.03b
Shannon-Wiener diversity index	0.72 ± 0.04a	0.5 ± 0.05b	0.33 ± 0.05b	0.72 ± 0.04a	0.3 ± 0.04b	0.27 ± 0.05b
Natural enemies						
Abundance	17.72 ± 6.27a	78.51 ± 10.79b	200.49 ± 23.79c	63.5 ± 10.01a	210.33 ± 24.90b	341.16 ± 39.72c
Margalef richness index	0.37 ± 0.18a	0.48 ± 0.26b	0.47 ± 0.19b	0.49 ± 0.09a	0.6 ± 0.06b	0.68 ± 0.04b
Evenness	0.36 ± 0.04a	0.47 ± 0.02b	0.47 ± 0.02b	0.58 ± 0.02a	0.67 ± 0.01b	0.67 ± 0.01b
Shannon-Wiener diversity index	0.51 ± 0.08a	0.69 ± 0.06b	0.74 ± 0.06b	0.92 ± 0.05a	1.16 ± 0.05b	1.19 ± 0.05b

The generalized mixed effect model generated means. Different alphabets show significant differences in row-wise comparisons adjusted using the Least significant difference (LSD) test at a 5% level of significance.

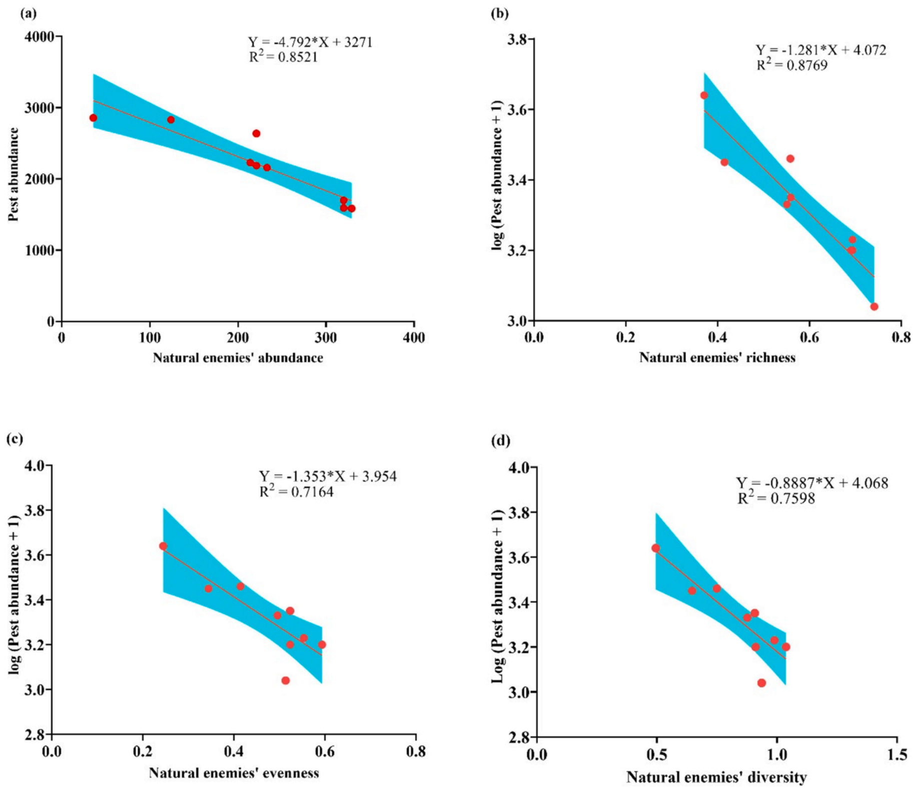

Fig. 2. Relationships between the pest (aphid) abundance and (a) natural enemies' abundance (b) richness, (c) evenness and (d) diversity in three copping systems of wheat and canola in years 2021.

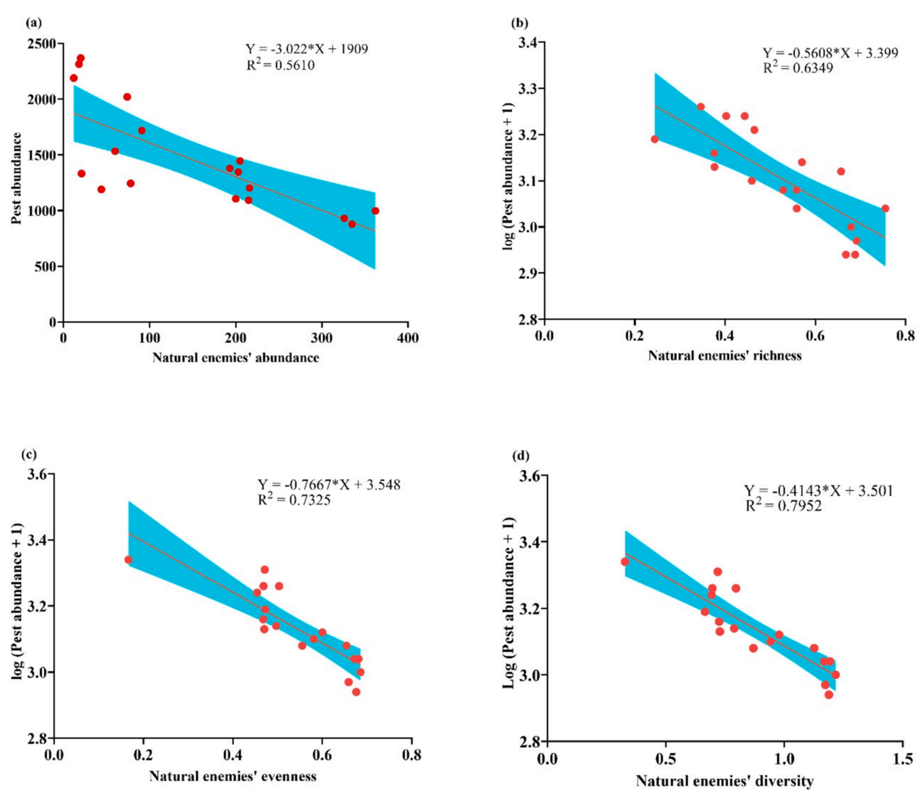

Fig. 3. Relationships between the pest (aphid) abundance and (a) natural enemies' abundance (b) richness, (c) evenness and (d) diversity in three copping systems of wheat and canola in years 2023.

hypothesis" which states that enhancement in local resource diversity facilitates a higher number and diversity and hence a higher dominance of natural enemies (Le Provost et al., 2023; Root, 1973; Russell, 1989). The resources that might have supplemented biological control agents in our research include food/alternative prey (canola aphids, which being species-specific do not infest wheat), shelter and space to live and reproduce (Gurr et al., 2016; Wan et al., 2018a; Wan et al., 2018b). Natural enemies like parasitoids, green lacewings, and hoverflies all depend on flower resources such as nectar and/or pollens for sugars and/or proteins (Lundgren, 2009; Wäckers & Van Rijn, 2012). We expected that said resources have been provided by added canola plants (Almdal & Costamagna, 2023). Parasitism rate has been reported to be directly proportional to the density of canola plants in a landscape due to the provision of carbohydrates in the form of honeydew secreted by the aphids, and mainly by floral nectars (Kheirodin et al., 2020). Nectars of canola flowers have been proven to be better diet than honeydew of aphids, and other flowering plants, e.g. sweet alyssum (*Lobularia maritima* L., Brassicaceae), buckwheat (*Fagopyrum esculentum* Moench, Polygonaceae), coriander (*Coriandrum sativum* L., Apiaceae), or phacelia (*Phacelia tanacetifolia* Benth, Boraginaceae) in terms of increasing longevity of aphid parasitoids (Varennes et al., 2016). Similarly, pollens of canola flowers increase the fecundity and longevity of hoverflies and other predators (Lu et al., 2014).

Honeydew can also increase the movement of predators from canola to the main crop (which in our case is wheat) in search of resources when canola matures and resources become scarce (Almdal & Costamagna, 2023). This is because canola matures earlier than wheat so natural enemies tend to move into wheat for foraging at later stages of development. This movement in our diversified systems is evident from a higher abundance of natural enemies in strip cropping and alternate-row intercropping compared with sole wheat since movement and density can be positively correlated (Almdal & Costamagna, 2023). In diversified cropping, canola bloomed before wheat pests started to increase in number so natural enemies were present in advance when the populations of wheat pests started to rise. This observation is consistent with previous studies (Almdal & Costamagna, 2023; Tian et al., 2022). This is important in heterogeneous fields which are meant to provide biological control services (Pfiffner et al., 2019; Porcel et al., 2017). Thus, crop heterogeneity provides an indirect "top-down" effect through natural enemies on herbivory by reducing pest population at the farm level (Barnes et al., 2020; Tscharntke et al., 2021; Yang et al., 2021) as predicted by the Tilman's (1982) resource complementation/supplementation process (Dunning et al., 1992). Wan et al. (2020) and Fahrig et al. (2011) proved that the addition of plant species with supplementary resources increases the performance of natural enemies which decreases the performance, density and diversity of herbivores. Our findings also support these conclusions as increase in natural enemies' diversity indices was associated with a decrease in aphid abundance in our experiments (Figs. 2 and 3).

We observed the lowest herbivore and greatest natural enemy abundances in alternate-row intercropping. This diversification pattern offers more plants of canola, and ultimately more flowers compared to strip crops. In addition, distance between flowering strips is reduced. Previous studies report that increasing flower diversity enhances natural enemy abundance (Alcalá Herrera et al., 2022; Serée et al., 2022) and limiting distances to flowering strips is key for biological control (Albrecht et al., 2020). Predation rates have been observed to be lower in the centre of plots when added crop is only present at the edges (strip cropping) and not near the central region (Han et al., 2022). An increased proportion of canola plants can also favour species-specific aphids viz., *Brevicoryne brassicae* (L.), *Lipaphis erysimi* (Kaltenbach) and *Myzus persicae* (Sulzer) (Aslam & Razaq, 2007) representing alternate prey for generalist predators. Alternate prey resources have been proven to support greater densities of generalist predators (Kheirodin et al., 2020; Kujawa et al., 2018).

The increased richness and abundance of natural enemies observed in strip and alternate-row intercropping, compared to the sole cropping, were a strong predictor of pest suppression. Coefficients from our regression analysis have biological significance. The slope, in particular, indicates the rate at which pest suppression improves with increasing density or richness of natural enemies. Increasing natural enemy abundance by 100 individuals led to about 20 % decrease of pest abundance on average in 2021 and decrease of about 22 % on average in 2023. By analysing regression coefficients, one could identify critical thresholds at which natural enemy populations are abundant enough to keep pests under a given threshold. More data on natural enemy-pest abundance relationships would be needed to build a robust model to be used as a decision support system. Yet, our results indicate that maintaining or enhancing the abundance and richness of natural enemies in agricultural systems can effectively keep pest populations under control. Farmers can monitor natural enemy populations and take steps to ensure their conservation and augmentation, thereby sustaining pest suppression below economic thresholds. Enhanced natural enemy species richness can promote successful pest resource utilization (Katano et al., 2015) by improving niche differentiation, especially when natural enemies with different feeding behaviours complement one another (Straub et al., 2008). The niche complementarity model emphasises the importance of species-rich ecosystems, with cumulative impacts on pest mortality due to the reduction of natural enemy-free space as natural enemies occupy different niches and feed on multiple types of pest species (Alhadidi et al., 2018; Hurd, 2008). In such environments, predators preying at different times or on different pest groups or engaging in complementary interactions because of differing hunting behaviours, result in predator niche differentiation. This differentiation, in turn, leads to enhanced biological control and complementary pest mortality (Michalko et al., 2019). This is also in accordance with the lottery model in which greater species richness enhances the possibility of superior biocontrol agents which dominate in community due to their higher evenness like ladybird beetles, hoverflies or lacewings (Evans, 2016; Hatfield & Chesson, 1997).

We expect that this biocontrol by increased dominance of some natural enemies in diverse systems can be attributed to multiple mechanisms. For instance, pea aphids produced a greater ratio of winged forms responding to the trails previously left by coccinellid larvae, which allowed them to evade predation by dispersing themselves off the vulnerable sites, leading to decreased aphid abundance and fecundity (Dixon & Agarwala, 1999). An important aspect of biocontrol is facilitated predation by dominant natural enemies' species which may increase (additive effects/synergism) the efficiency of biological control by influencing top-down control of pests achieved through trophic cascades. So, in our case increased abundance and evenness of natural enemies might have established positive guilds leading to decreased abundance and evenness of aphids. Furthermore, higher enemy evenness can lead to the occupation of multiple complementary feeding niches such that no unoccupied niches are left (Hamza et al., 2023; Snyder, 2019). This decreases dominance of pests explaining that biological control often increases in diverse cropping systems (Root, 1973). Beyond the top-down control operated by natural enemies, diversified cropping system, like strip cropping and intercropping, can also regulate pest populations through bottom-up effects (Han et al., 2022). The lower aphid density in the diverse wheat fields might be attributed to visual hindrances created by the taller canola plants compared to wheat and through volatile mixtures of both crops. Aphids are known to use indicators of vision (such as colours, contrasts, and host morphology) when looking for their host species (Döring, 2014) hence non-host canola strips may have masked wheat plants through their height (Finch & Collier, 2000).

4.2. Diversifying organic farming

We found a greater abundance and diversity of natural enemies in organic farming fields compared to conventional ones, which is consistent with previous studies (Muneret et al., 2018). Here, we demonstrate that diversifying organic cropping systems with strip and alternate-row intercropping strengthens biological control. Our study supports the conclusion drawn from a synthesis of meta-analyses that sole organic farming has a limited capability in providing biocontrol services, even at the expense of reduced productivity (Tscharntke et al., 2021). This literature synthesis also advocated that in comparison to the shift from organic to conventional farming, diversifying agroecosystems through the implementation of heterogeneous cropping systems can not only foster biological control agents but also provides acceptable yield irrespective of the farm type.

4.3. Perspective: Enhancing and stabilizing productivity

We did not explore the wheat yield parameter in our experiment. Wheat crop may have benefited from the canola plants leading to an enhanced productivity. Canola glucosinolates can help wheat against pathogens like *Rhizoctonia solani* and *Fusarium* spp. This disrupts disease patterns of wheat (Kutcher et al., 2011; Smith et al., 2004). Allelopathic chemicals of canola suppress the broad leaf weeds of wheat. Additionally, canola's rapid growth and thick canopy outcompete weeds for resources (Asaduzzaman et al., 2014; Shah et al., 2016). Canola may also foster nutrients to wheat through increased organic matter. Canola can benefit from an endophytic diazotroph, *Paenibacillus polymyxa*, capable of fixing nitrogen reducing N requirements of wheat. Furthermore, canola parts decompose quickly, releasing nitrogen available for adjacent wheat crops (Puri et al., 2016; Soon & Arshad, 2002). Canola's deep taproot system, which can penetrate hardpans compared to wheat which has fibrous roots, can improve aeration and drainage for wheat (Chen & Weil, 2010; Kirkegaard et al., 2020).

Furthermore, canola can be considered as a secondary crop with wheat, providing additional resources like edible oil and seed meal (source of protein for poultry and livestock) (Lin et al., 2013; Wickramasuriya et al., 2015; Zhu et al., 2014). It can represent an insurance in case wheat crop (partially) fails, which would even benefit from compensation effects (Döring & Elsalahy, 2022). This economic diversification can account for worries of reduction in wheat productivity and can ease the adoption of strip and intercropping. Lower gains are of the main concerns of the farmers in adopting intercropping for the provision of biological control services (Huss et al., 2022). So, this is particularly important for countries, like Pakistan, that are heavily dependent on imported edible oil to meet their local requirements (Joshi et al., 2004; Rana et al., 2022; Sheil et al., 2009).

5. Conclusion

This research highlights the potential of utilizing ecological intensification approaches to manage insect pests in agricultural systems. We found that wheat-canola strip cropping and alternate-row intercropping significantly reduced wheat aphid abundance compared to wheat sole cropping. These diversified systems fostered higher densities and diversities of natural enemies, which in turn contributed to the effective biological control. The increased richness and evenness of natural enemies within the diversified cropping systems suggests a complex ecological interplay through complementarity and functional redundancy that enhances pest suppression. As our experiment was limited to experimental plots, further research is needed to explore the long-term economic feasibility, practicality and impacts of these practices on wheat yield at large and broader field scales. Collectively, we provide evidence that by integrating diverse practices into farming systems, we can promote a more sustainable and resilient approach to agricultural pest management.

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CRediT authorship contribution statement

Sohaib Saleem: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Muhammad Omer Farooq:** Writing – review & editing, Formal analysis. **Muhammad Razaq:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Séverin Hatt:** Writing – review & editing. **Farhan Mahmood Shah:** Writing – review & editing, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2024.105677.

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