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Arthropod diversity and trophic balance in monoculture and polyculture rice fields in Mardingding, Karo, North Sumatra, Indonesia

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Abstract. *Ginting TY, Triwidodo H, Winasa IW, Maryana N. 2026. Arthropod diversity and trophic balance in monoculture and polyculture rice fields in Mardingding, Karo, North Sumatra, Indonesia. Biodiversitas 27 (5): d270502. https://doi.org/10.13057/biodiv/d270502.* This study evaluated the temporal dynamics and functional balance of arthropod communities in monoculture and polyculture rice systems across two cropping seasons in Mardingding Sub-district, Karo District, North Sumatra, Indonesia. Polyculture refers to rice fields in which diversification was implemented primarily through companion vegetation on bunds or surrounding field margins, whereas monoculture consisted of rice grown without such border vegetation. Weekly arthropod sampling was conducted from planting to harvest in six farmer-managed paddy fields using a portable suction sampler. Arthropods were identified as morphospecies and classified into functional guilds. Community structure was assessed using Shannon-Wiener diversity (H′), Pielou's evenness (E), and Simpson's dominance (D) indices and analyzed using GLM repeated-measures ANOVA, in which fields were treated as independent experimental units (n: 6), temporal observations were modeled as repeated measures within fields, and cropping season was included as a within-subject factor. Temporal patterns showed that diversity and evenness increased toward mid-season and declined near crop maturity, whereas dominance showed the opposite trend. The cropping system had a significant effect on diversity (F(1, 4): 18.86, p: 0.012, partial η^2: 0.825), whereas the cropping season was not (p: 0.095). The interaction between the cropping system and season was also not significant. Evenness was significantly influenced by cropping season (F(1, 4): 12.44, p: 0.024, partial η^2: 0.757), while no significant effects were detected for dominance. Paired comparisons at the field level indicated higher diversity in polyculture during Season 1, whereas differences were not significant in Season 2. Polyculture fields also showed higher natural enemy-to-pest ratios than monoculture. These findings suggest that crop diversification through bund-associated vegetation was associated with a higher relative abundance of natural enemies and may contribute to shifts in trophic structure within rice agroecosystems.

Keywords: Arthropod community, biological control, functional balance, natural enemy-to-pest ratio, *Oryza sativa*

INTRODUCTION

Rice agroecosystems are dynamic systems in which crop productivity is closely linked to arthropod community structure (Triwidodo et al. 2023). Arthropods play multiple ecological roles as herbivores, biological control agents, decomposers, and regulators of trophic interactions (Matteson 2000; Ali et al. 2019). Thus, ecosystem functioning depends not only on species richness but also on the balance among functional groups (Ali et al. 2022). Disruptions in this balance may weaken trophic regulation and increase vulnerability to pest outbreaks, particularly in simplified systems (van den Bosch and Stern 1962; Cabasan et al. 2019).

Cropping configuration is a key driver of habitat complexity and resource distribution in rice fields (Magurran 2021; Raut et al. 2023). Monoculture systems provide uniform vegetation and synchronized phenology, conditions that may favor herbivorous pests while reducing habitat heterogeneity for natural enemies. In contrast, diversification can enhance structural complexity and resource continuity, expand niche availability, and stabilize trophic interactions (Horgan et al. 2019; Bevilacqua et al. 2021). In farmer-managed rice systems, diversification often occurs through vegetation along bunds and field margins rather than mixed cropping within the field. In this study, polyculture refers to rice fields accompanied by companion vegetation on bunds and borders, including vegetables and flowering plants such as chili (*Capsicum annuum*), eggplant (*Solanum melongena*), and long bean (*Vigna unguiculata*). These plants may provide nectar, alternative prey, and microhabitats, unlike bare or weed-cleared bunds in monoculture systems.

Despite increasing promotion of ecological intensification, evidence from farmer-managed rice systems that integrate taxonomic diversity and functional organization remains limited (Bevilacqua et al. 2021; Dominik et al. 2022). Most studies use Shannon-Wiener diversity (H'), Pielou's evenness (E), and Simpson's dominance (D) to describe community structure (Xu et al. 2024). Although these indices capture richness and relative abundance, they may not fully reflect ecological stability or regulatory potential. Communities with similar diversity values can differ in trophic composition and functional roles. Therefore, combining diversity metrics with functional guild classification provides a comprehensive assessment of agroecosystem resilience (Makwela et al. 2023). Morphospecies-based identification also offers a consistent field-scale approach (Derraik et al. 2010).

Functional balance, particularly the relationship between natural enemies and herbivorous pests, is central to sustainable pest management. The natural enemy-to-pest (NE:P) ratio is widely used as an indicator of potential biological control, with higher ratios suggesting regulatory capacity (Yunus et al. 2022; Bonato et al. 2023). However, these relationships are dynamic and influenced by time. Arthropod communities in rice fields change throughout the cropping cycle in response to plant phenology and climate (Gutiérrez and Wilson 2021). Therefore, single-time-point observations may fail to capture community assembly, whereas longitudinal sampling provides a stronger framework for understanding these dynamics (Lu et al. 2022).

Although sustainability-oriented approaches are increasingly emphasized (Ibrahim et al. 2025), longitudinal comparisons between monoculture and bund-associated polyculture systems under farmer management remain scarce. Few studies simultaneously evaluate diversity indices, functional guild structure, and temporal dynamics across multiple cropping seasons in tropical systems. Addressing this gap is essential for understanding whether farmer-led diversification influences arthropod community assembly and natural enemies.

This study addresses these limitations by conducting a two-season, field-replicated longitudinal assessment of arthropod communities in monoculture and polyculture rice systems. Arthropods were sampled weekly using a motorized suction device (farmcop-type) to capture canopy-dwelling species. A repeated-measures analytical framework was applied to account for temporal autocorrelation, while functional balance was evaluated using a guild-based NE:P (Natural Enemy-to-Pest) ratio. This integrative approach allows for a detailed examination of both taxonomic and functional dimensions of biodiversity in relation to cropping systems and season.

Therefore, this study aimed to evaluate the temporal dynamics and functional organization of arthropod communities in monoculture and polyculture rice systems across two consecutive cropping seasons. Specifically, we (i) compared diversity, evenness, and dominance indices between cropping systems and seasons; (ii) examined seasonal changes in functional guild composition; and (iii) quantified functional balance using the NE:P ratio. By integrating taxonomic and functional perspectives, this study provides empirical evidence on how bund-associated crop diversification in farmer-managed systems influences arthropod community structure and ecological functioning.

MATERIALS AND METHODS

Study area and period

The study was conducted during two consecutive rice cropping seasons in 2025 in Mardingding Sub-district, Karo District, North Sumatra, Indonesia (3.2802° North, 97.9817° East). The region comprises a tropical lowland rice agroecosystem at approximately 200-250 m above sea level, characterized by a humid tropical climate with relatively stable temperatures (23-30°C) year-round. Annual rainfall ranges from approximately 2,000 to 2,500 mm, with rainfall distributed throughout the year but typically peaking between October and December. Field sampling was conducted during the active cropping period, while the post-harvest months (October-December 2025) were used for specimen identification, data processing, and statistical analysis.

Rice cultivation in the area follows a semi-annual cropping cycle, allowing two cropping seasons per year. The first cropping season was conducted from January to April 2025, while the second cropping season was conducted from July to September 2025. The surrounding landscape consists primarily of rice fields interspersed with smallholder vegetable farms, fallow land, irrigation canals, and patches of secondary vegetation along field margins. These heterogeneous landscape elements may provide alternative habitats and resources for arthropod communities.

Six independent rice fields were selected as study sites, representing two cropping systems: monoculture and polyculture. Three spatially separated fields located in Lau Pakam, Lau Solu, and Bandar Purba villages represented monoculture systems. In comparison, three fields located in Lau Kasumpat, Mardingding, and Tanjung Pamah villages represented polyculture systems. Each field ranged between 0.25 and 0.40 ha and was managed by different farmers. This study was designed as a field-based observational comparison under real farmer-managed conditions rather than a fully controlled experiment, with each field serving as an independent experimental unit representing its respective cropping system.

All selected fields cultivated the same rice variety (Ciherang) and followed broadly similar transplanting schedules within each cropping season. However, agronomic practices such as fertilization, organic manure application, and pesticide use were determined independently by farmers and were not standardized or quantitatively recorded. Fertilization generally involved urea (150-200 kg ha^{-1}), NPK compound fertilizer (100-150 kg ha^{-1}), and organic inputs when available, while pest management typically included one to two insecticide applications per season using pyrethroid- or neonicotinoid-based products. Irrigation was supplied through local canal systems and maintained during the vegetative stage. Because management practices were not experimentally controlled, observed differences between cropping systems should be interpreted as associations under farmer-managed conditions rather than strictly causal effects. However, the use of multiple independent fields per system allows for comparison across representative agroecosystem contexts.

Definition of cropping systems

The primary experimental factor in this study was the cropping system (monoculture vs polyculture). In monoculture fields, rice was cultivated as a single crop species across the entire field without additional plant species intentionally introduced within field margins or bunds. In contrast, polyculture fields consisted of rice cultivation combined with companion plant species grown along field bunds and borders. These companion plants included vegetables and flowering species commonly cultivated by farmers in the region, such as chili (*C. annuum*), eggplant (*S. melongena*), long bean (*V. unguiculata*), and several flowering plants used for household consumption. Companion vegetation was typically planted in narrow strips along field margins or bunds surrounding the rice plots, occupying approximately 5-10% of the total field area. Although rice remained the dominant crop species within the cultivated area, the presence of additional plant species increased vegetation heterogeneity, potentially providing floral resources, shelter, and alternative prey for beneficial arthropods.

Procedures

Sampling design and experimental unit

The study was conducted in monoculture and polyculture rice fields planted with the widely cultivated Ciherang variety, one of the most commonly grown rice cultivars in Indonesia. Arthropods were sampled directly from rice plants using a modified plant-level suction device (farmcop), designed to capture arthropods actively inhabiting the crop canopy. Plant-level suction sampling is widely used for assessing pest and natural enemy assemblages in rice ecosystems because it provides a targeted representation of canopy-dwelling arthropods and reduces biases associated with passive trapping methods (Horgan et al. 2019).

The study employed a hierarchical sampling design comprising fields, subplots, and repeated temporal observations. Six independent fields served as the primary experimental units, with three replicate fields per cropping system. Within each field, three sampling subplots were established to account for spatial heterogeneity in arthropod distribution. Subplots were positioned diagonally across the field to capture within-field variability, a spatial arrangement commonly recommended in agroecological studies. Repeated observations were conducted across multiple sampling dates within each subplot to characterize temporal dynamics. For inferential statistical analyses, field-level means were used as the unit of replication to avoid pseudo-replication. In contrast, subplot- and time-level data were used to describe within-field spatial and temporal variation (Altieri et al. 1999; Ali et al. 2022).

Each subplot consisted of 16 rice hills arranged in a 4×4 grid configuration. Therefore, a total of 48 rice hills were sampled in each field during every sampling event. Sampling was conducted weekly from one week after transplanting until crop maturity, resulting in 12 sampling occasions per cropping season. The same fields and subplot locations were monitored across both cropping seasons to enable longitudinal comparisons. This sampling intensity was selected to balance spatial coverage and sampling efficiency, and is consistent with previous studies examining arthropod communities in rice agroecosystems. All observations were subsequently aggregated to the field level for inferential statistical analyses, ensuring consistency with the experimental unit (Horgan et al. 2017; Chen et al. 2023).

To avoid pseudo-replication in statistical analyses, observations from subplots within each field were averaged to obtain field-level values at each sampling week. These repeated measurements were used to characterize the temporal dynamics of arthropod communities across the cropping cycle. For inferential comparisons between cropping systems, field-level means aggregated across sampling weeks were used, ensuring that the field represented the true experimental replicate. The resulting data structure consisted of 6 fields (experimental units), 12 sampling weeks per season, and 2 cropping seasons, with each field contributing a repeated time series of arthropod community measurements.

To minimize arthropod escape during suction sampling, each subplot was temporarily enclosed with a fine-mesh cage before collection (Figure 1). The enclosure ensured that highly mobile taxa, including predators and flying insects, were retained within the sampling unit, thereby improving capture efficiency and reducing underestimation of canopy-active species (Altieri et al. 1999; Ali et al. 2023). After sampling, enclosures were removed, and subplot boundaries were marked using lightweight plastic fencing to ensure that the same sampling locations were consistently monitored throughout the study. This permanent marking enabled repeated observations across crop growth stages and between consecutive cropping seasons, facilitating robust temporal comparisons of arthropod community dynamics.

Suction sampling procedure

Arthropods were collected using a modified suction sampler (farmcop-type device) designed for plant-level arthropod collection in rice canopies. The device operated at a standardized suction pressure of approximately 20,000 Pa. This device was equipped with a suction nozzle approximately 5 cm in diameter. Before each sampling event, the suction device was calibrated to ensure consistent airflow and capture efficiency. During sampling, the nozzle was carefully moved around the rice canopy, approximately 5-10 cm from the plant surface, to collect arthropods inhabiting leaves, stems, and upper canopy structures.

Each subplot was vacuumed for a standardized 5-minute duration. This sampling duration was selected based on previous studies of rice arthropod communities using suction methods and was considered sufficient to capture canopy-dwelling arthropods while maintaining consistency across plots (Horgan et al. 2019). Sampling was conducted between 08:00 and 11:00 local time to minimize variation caused by diel activity patterns of arthropods. Sampling was not performed during rainfall or strong winds to avoid bias. To prevent arthropod escape during sampling, each subplot was temporarily enclosed with a fine-mesh cage before suction collection. After sampling, cages were removed, and subplot boundaries were marked to ensure consistent sampling locations throughout the study.

Arthropod identification and functional guild classification

All collected specimens were preserved in 70% ethanol and transported to the Laboratory of Insect Biosystematics, Department of Plant Protection, Institut Pertanian Bogor, for identification. Specimens were initially sorted to order and family levels using standard taxonomic keys and reference collections. Whenever possible, individuals were further distinguished into morphospecies based on diagnostic external morphological characteristics observed under a stereomicroscope (Hidayat et al. 2019). The morphospecies approach provides a practical and widely accepted method for biodiversity assessment in ecological studies where full species-level identification may be constrained by taxonomic limitations (Derraik et al. 2010; Bevilacqua et al. 2021).

Each morphospecies was subsequently assigned to a functional guild based on ecological traits and feeding behavior documented in the literature. Functional guilds included: (i) primary pests: herbivorous species directly feeding on rice plants; (ii) other herbivores: plant feeders not considered major rice pests; (iii) predators: arthropods feeding on other arthropods; (iv) parasitoids: insects whose larvae develop within or on host insects; (v) decomposers/detritivores: species feeding on decomposing organic material; (vi) vectors: arthropods known to transmit plant pathogens affecting rice crops. The guild assignment followed published ecological classifications and regional entomological references (Hidayat et al. 2025).

Data analysis

Community structure analysis

Arthropod community structure was evaluated for each sampling week and cropping season using complementary ecological indices describing diversity, evenness, and dominance. All indices were calculated based on morphospecies-level abundance data for each field and sampling occasion.

Species diversity was quantified using the Shannon-Wiener diversity index (H′), calculated as equation 1:

$$H' = -\sum_{i=1}^{S} pi \cdot \ln pi \qquad [1]$$

Where, S represents the total number of morphospecies and p_i is the proportional abundance of the *i*th morphospecies relative to the total number of individuals in the sample. The Shannon-Wiener index incorporates both species richness and relative abundance, making it sensitive to changes in rare and common taxa. This index is widely applied in agroecological studies to detect shifts in arthropod community complexity across management systems and temporal gradients (Magurran 2021).

Community evenness was assessed using Pielou's evenness index (E), expressed as equation 2:

$$E = \frac{H'}{\ln S} \qquad [2]$$

This index standardizes Shannon diversity relative to the maximum possible diversity at a given richness level, providing a measure of how evenly individuals are distributed among morphospecies. Values approach 1 when abundances are evenly distributed and decline as communities become increasingly uneven (Pielou 1966).

Dominance patterns were evaluated using Simpson's dominance index (D), calculated as equation 3:

$$D = \sum_{i=1}^{S} pi^2 \qquad [3]$$

Simpson's index emphasizes the influence of the most abundant taxa and reflects the probability that two randomly selected individuals from a sample belong to the same morphospecies. Higher values of D indicate stronger dominance by one or a few morphospecies, whereas lower values represent more equitable community composition (Simpson 1949).

All indices were calculated separately for each field and sampling week, and seasonal means were subsequently derived for comparative analysis between cropping patterns. The combined application of diversity (H′), evenness (E), and dominance (D) metrics provides a multidimensional characterization of community organization. Integrating these complementary indices enables a more comprehensive interpretation of temporal dynamics, structural complexity, and potential ecological stability in rice agroecosystems.

Figure 1. Arthropod sampling using a Farmcop suction sampler in rice fields. The image illustrates the sampling configuration in which rice hills are enclosed in a mesh cage to prevent arthropods from escaping during suction, ensuring standardized, consistent collection from defined sampling units

Functional balance assessment

Functional balance within the arthropod community was evaluated using the natural enemy-to-pest ratio (NE:P). Natural enemies included morphospecies classified as predators and parasitoids, while pests comprised morphospecies identified as primary rice herbivores. The natural enemy-to-pest ratio (NE:P) in equation 4 was computed as the total abundance of predators and parasitoids divided by the total abundance of pest individuals for each sampling unit. The NE:P ratio was calculated as:

$$Ne:P = \frac{Predators+Parasitoids}{Pests} \quad [4]$$

This metric represents the relative abundance of regulatory trophic groups compared with herbivorous pest populations. For statistical comparisons of functional composition between cropping systems, the proportion of natural enemies among the combined pool of natural enemies and pests (NE / (NE + Pest)) was also calculated. This proportional metric allows direct statistical comparison of trophic structure between systems.

The NE:P ratio was first calculated for each weekly sampling event and subsequently averaged at the seasonal level to facilitate comparison between cropping patterns. Integrating functional balance metrics with diversity indices allows assessment of whether differences in taxonomic structure correspond to shifts in trophic organization (Sinaga et al. 2024). Such a combined evaluation strengthens ecological interpretation by linking community composition with potential biological control capacity and contributes to a more function-oriented assessment of rice agroecosystem stability.

The NE:P ratio provides a community-level indicator of trophic structure and the relative representation of regulatory versus herbivorous guilds within the agroecosystem. Higher NE:P values indicate a greater proportional abundance of natural enemies relative to pests, suggesting stronger potential for intrinsic biological regulation. Conversely, lower values reflect pest-dominated assemblages and may indicate reduced regulatory buffering capacity. Although the NE:P ratio does not directly quantify predation or parasitism rates, it serves as a practical proxy for evaluating the balance between antagonistic trophic groups under field conditions (Symondson et al. 2002; Ali et al. 2023).

Statistical analysis

Arthropod abundance data obtained from weekly field observations were compiled and organized for each sampling unit before statistical analysis. Preliminary data tabulation, calculation of descriptive statistics, and graphical summaries were prepared using Microsoft Excel (Microsoft Corp., Redmond, WA, USA). All statistical analyses were subsequently conducted using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). Statistical significance for all tests was determined at the 95% confidence level (α: 0.05).

The structure of the arthropod community associated with rice plants was evaluated using several ecological indices. Species diversity was calculated using the Shannon-Wiener diversity index (H′), dominance was assessed using the Simpson dominance index (D), and species evenness was estimated using Pielou's evenness index (E). These indices were used to characterize patterns of species diversity, dominance, and distribution within each cropping system and to provide a quantitative basis for comparing arthropod community structure throughout the rice-growing season.

To evaluate temporal changes and treatment effects, differences in diversity indices between cropping systems across observation periods were analyzed using a General Linear Model (GLM) repeated-measures ANOVA. This analytical approach enabled simultaneous assessment of temporal dynamics and treatment effects on arthropod community structure during the rice-growing season. Before conducting the repeated-measures analysis, the assumption of sphericity was assessed using Mauchly's test. When the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied to adjust the model's degrees of freedom. This analytical framework enabled robust statistical inference for repeated observations across the cropping cycle.

In addition to the repeated-measures analysis, paired samples t-tests were conducted to compare diversity indices between monoculture and polyculture systems within each cropping season. This approach was applied because fields from the two cropping systems were matched based on comparable site characteristics, allowing direct comparison of paired field-level values. The tests evaluated whether the mean differences in diversity indices (H′, E, and D) between the two cropping systems were statistically significant within each season. Standardized effect sizes were calculated using Cohen's d to quantify differences between cropping systems. Effect sizes were interpreted according to Cohen's (1988) benchmarks: small: 0.2, moderate: 0.5, and large: 0.8.

To evaluate the potential for natural biological control within the rice agroecosystem, the natural enemy-to-pest ratio (NE:P) was calculated as the abundance of natural enemies divided by the abundance of herbivorous pests. Natural enemies included predators and parasitoids (egg, larval, and other parasitoids). The NE:P ratio was used as an indicator of the balance between beneficial arthropods and pest populations within each cropping system, where higher values indicate a greater relative abundance of natural enemies and thus stronger potential for natural pest regulation.

In addition to the NE:P ratio, the proportion of natural enemies within the arthropod community was calculated to describe the relative dominance of beneficial arthropods. This proportion was expressed as NE / (NE + P), where NE represents the abundance of natural enemies, and P represents the abundance of herbivorous pests. Proportions were first calculated for each field using seasonal totals derived from weekly observations, and mean values with standard errors were then calculated across fields within each cropping system. This field-level approach was used to account for variability among sampling fields when comparing the relative contribution of natural enemies to pest populations. Seasonal totals were obtained by summing weekly observations within each field during the sampling period.

RESULTS AND DISCUSSION

Temporal dynamics of arthropod community structure

Arthropod community structure exhibited pronounced temporal dynamics across weeks after transplanting (WAT) in both monoculture and polyculture systems during the two cropping seasons (Figures 2 and 3). In general, the Shannon diversity index (H′) and Pielou evenness (E) increased from the early vegetative stage toward the mid-season period. Subsequently, they declined toward the end of the cropping cycle. Conversely, Simpson dominance (D) showed an inverse pattern, with relatively higher values during the early weeks when a few species still dominated community composition.

Monoculture system

In the monoculture system, arthropod diversity increased progressively from the early growth stage. During the first cropping season, the Shannon diversity index increased from 0.79±0.45 at 1 WAT to a peak of 2.33±0.13 at 6 WAT, before gradually declining toward 1.29±0.02 at 12 WAT (Figure 2). A similar temporal trend was observed during the second season, where diversity increased from 0.87±0.16 at 1 WAT and reached its maximum value at 10 WAT (2.22±0.07) before declining toward 1.42±0.04 at 12 WAT. Evenness followed a comparable pattern, increasing from 0.21±0.12 at 1 WAT to peak values during the mid-season period (0.64±0.05 at 6 WAT in season 1 and 0.67±0.06 at 9-10 WAT in season 2), indicating a more balanced distribution of arthropod species. Toward the late growth stage, evenness declined to 0.35±0.02 and 0.43±0.01 at 12 WAT for seasons 1 and 2, respectively. In contrast, dominance values were highest during the early growth stage. Simpson dominance ranged from 0.26±0.16 to 0.47±0.11 at 1 WAT, decreased to minimum values during the mid-season (0.11±0.01 at 6-9 WAT in season 1 and 0.12±0.01 at 10 WAT in season 2), and increased again toward the end of the cropping cycle (0.26±0.01 at 12 WAT).

Polyculture system

Temporal patterns of arthropod community structure in the polyculture system showed similar seasonal dynamics but generally exhibited higher diversity levels during the mid-season period (Figure 3). During the first cropping season, diversity increased from 1.40±0.47 at 1 WAT to a maximum value of 2.67±0.04 at 5 WAT, before gradually declining toward 1.80±0.11 at 12 WAT. In the second season, diversity increased from 0.74±0.74 at 1 WAT to peak values of approximately 2.42±0.20 at 4-6 WAT, followed by moderate fluctuations before declining toward 1.56±0.17 at 12 WAT. Evenness also increased during the early growth stages and reached its highest values during mid-season. In season 1, evenness increased from 0.33±0.10 at 1 WAT to 0.63±0.02 at 5 WAT. In contrast, in season 2, it increased from 0.17±0.17 at 1 WAT to 0.61±0.10 at 4-6 WAT, indicating a relatively balanced species distribution during the peak arthropod activity period. Dominance values showed the opposite trend, declining from relatively high values at the beginning of the season (0.35±0.10 in season 1 and 0.39±0.39 in season 2 at 1 WAT) to minimum values during mid-season (0.09±0.01 at 5 WAT in season 1 and 0.13±0.03 at 4-6 WAT in season 2), before increasing again toward the late growth stage.

Overall, these results indicate that arthropod community structure in rice ecosystems was highly dynamic throughout the cropping season. Diversity and evenness generally peaked during the mid-season growth stages (approximately 4-10 WAT), whereas dominance was lowest during this period. Compared with monoculture, the polyculture system tended to exhibit higher peak diversity and lower dominance, suggesting a more balanced and stable arthropod community structure under diversified cropping conditions.

Effects of cropping system and season on diversity (H’)

Temporal patterns of the Shannon-Wiener diversity index (H’) across weeks after transplanting are illustrated in Figures 2 and 3. These figures show the weekly dynamics of arthropod diversity throughout the rice growing period. A GLM repeated-measures ANOVA was conducted to evaluate the main effects of cropping system and cropping season on overall diversity.

The results of the GLM-RM ANOVA are presented in Table 1. Cropping system had a significant effect on H′ (F(1, 4): 18.86, p: 0.012, partial η^2: 0.825), indicating that Shannon diversity differed significantly between monoculture and polyculture systems across the study period. The large effect size suggests that the cropping system accounted for a substantial proportion of the variance in H′. In contrast, cropping season did not have a statistically significant effect on H′ (F(1, 4): 4.72, p: 0.095, partial η^2: 0.542), although the effect size indicates a moderate-to-large magnitude of seasonal variation. The interaction between cropping system and cropping season was also not statistically significant (F(1, 4): 2.18, p: 0.214, partial η^2: 0.352), suggesting that the influence of cropping system on diversity was relatively consistent across both cropping seasons.

Effects of cropping system and season on evenness (E)

Temporal fluctuations in Pielou’s evenness index (E) throughout the cropping cycle are also illustrated in Figures 2 and 3. These graphical patterns reflect changes in the relative distribution of arthropod species during different growth stages of the rice crop. The GLM repeated-measures ANOVA was used to test whether cropping system and cropping season significantly influenced overall evenness.

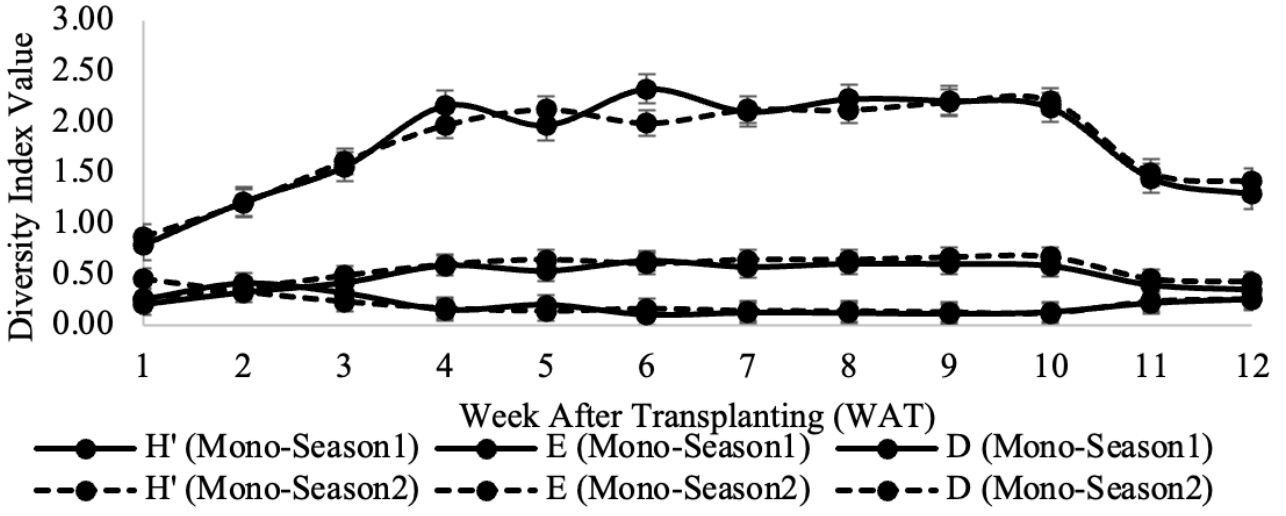

Figure 2. Temporal dynamics of arthropod diversity indices in the monoculture rice system across weeks after transplanting (WAT) during two cropping seasons. The figure shows weekly changes in Shannon diversity (H′), Pielou evenness (E), and Simpson dominance (D) from 1 to 12 WAT. Values represent mean±SE calculated from three independent fields per cropping system

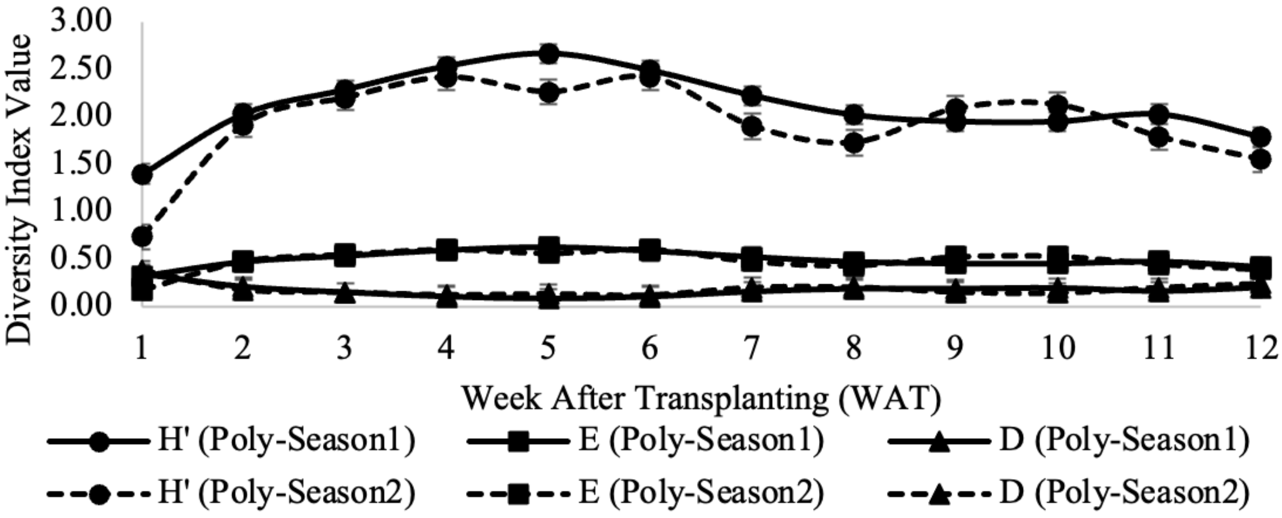

Figure 3. Temporal dynamics of arthropod diversity indices in the polyculture rice system across weeks after transplanting (WAT) during two cropping seasons. The graphs illustrate weekly variation in Shannon diversity (H′), Pielou evenness (E), and Simpson dominance (D) from 1 to 12 WAT. Values represent the mean±SE across three independent fields per cropping system

Table 1. Results of the GLM-RM ANOVA examining the effects of cropping system and cropping season on Shannon-Wiener diversity index (H')

Source	df	F	p	Partial η^2
Cropping system	1, 4	18.858	0.012	0.825
Cropping season	1, 4	4.724	0.095	0.542
Cropping system × cropping season	1, 4	2.177	0.214	0.352

Note: Degrees of freedom (df) are reported as numerator and denominator values. Partial η^2 indicates effect size. Analyses were conducted using field-level means, with each field treated as an independent experimental unit (n: 6). Because the within-subject factor contained two levels, the assumption of sphericity was automatically satisfied. Therefore, Greenhouse-Geisser and Huynh-Feldt corrections produced identical results

The results are summarized in Table 2. The cropping system did not have a statistically significant main effect on evenness (F(1, 4): 3.14, p: 0.151, partial η^2: 0.440), indicating that differences in evenness between monoculture and polyculture systems were not significant across the study period. However, the effect size suggests a moderate magnitude. In contrast, cropping season had a significant effect on evenness (F(1, 4): 12.44, p: 0.024, partial η^2: 0.757), indicating that seasonal variation accounted for a substantial proportion of the variability in E. The interaction between cropping system and cropping season was not statistically significant (F(1, 4): 0.01, p: 0.921, partial η^2: 0.003), suggesting that the effect of cropping system on evenness was consistent across both cropping seasons.

Effects of cropping system and season on dominance (D)

Temporal variations in Simpson's dominance index (D) across the cropping season are presented in Figures 2 and 3. These trends illustrate shifts in species dominance within arthropod communities during the rice growth cycle. To evaluate whether cropping system and cropping season influenced dominance levels, the data were analyzed using GLM repeated-measures ANOVA. The results are presented in Table 3. The cropping system did not have a statistically significant effect on dominance (F(1, 4): 7.09, p: 0.056, partial η^2: 0.639). However, the effect size indicates a large magnitude, suggesting a tendency for differences in dominance between monoculture and polyculture systems. Cropping season also showed no significant main effect on D (F(1, 4): 1.09, p: 0.356, partial η^2: 0.214), indicating that dominance did not differ substantially between the two cropping seasons. Similarly, the interaction between cropping system and cropping season was not statistically significant (F(1, 4): 1.88, p: 0.243, partial η^2: 0.319), suggesting that the combined influence of cropping system and season did not significantly explain variation in dominance values.

Seasonal comparison of cropping systems within each cropping season

Differences between cropping systems within each season on diversity (H')

Differences in Shannon-Wiener diversity (H') between monoculture and polyculture systems within each cropping season were evaluated using paired samples t-tests based on matched sampling units. The results are presented in Table 4. During the first cropping season, diversity differed significantly between monoculture and polyculture systems (t(2): -4.41, p<0.001). The mean difference was -0.328 (95% CI: -0.480 to -0.177), indicating that diversity in the monoculture was significantly lower than in the polyculture. The standardized effect size was moderate to large (Cohen's d: -0.735). In contrast, during the second cropping season, no significant difference in diversity was detected between cropping systems (t(2): -1.33, p: 0.191). The mean difference was -0.150 (95% CI: -0.382 to 0.079), and the confidence interval did not include zero. The effect size was small (Cohen's d: -0.222), indicating a weak difference between systems during the second season.

Differences between cropping systems within each season on evenness (E)

Differences in Pielou's evenness index (E) between cropping systems within each season were also evaluated using paired samples t-tests (Table 5). During the first cropping season, evenness did not differ significantly between monoculture and polyculture systems (t(2): -0.61, p: 0.544). The mean difference was -0.013 (95% CI: -0.055 to 0.030). The effect size was very small (Cohen's d: -0.102). Similarly, during the second cropping season, evenness also did not differ significantly between cropping systems (t(2): -1.80, p: 0.081). The mean difference was 0.055 (95% CI: -0.007 to 0.118). The effect size was small (Cohen's d: 0.299).

Table 2. Results of the GLM-RM ANOVA examining the effects of cropping system and cropping season on Pielou's evenness index (E)

Source	df	F	p	Partial η^2
Cropping system	1, 4	3.141	0.151	0.440
Cropping season	1, 4	12.439	0.024	0.757
Cropping system × cropping season	1, 4	0.011	0.921	0.003

Note: Degrees of freedom (df) are reported as numerator and denominator values. Partial η^2 indicates effect size. Analyses were conducted using field-level means, with each field treated as an independent experimental unit (n: 6). Because the within-subject factor contained two levels, the assumption of sphericity was automatically satisfied. Therefore, Greenhouse-Geisser and Huynh-Feldt corrections produced identical results

Table 3. Results of the GLM-RM ANOVA examining the effects of cropping system and cropping season on Simpson's dominance index (D)

Source	df	F	p	Partial η^2
Cropping system	1, 4	7.093	0.056	0.639
Cropping season	1, 4	1.088	0.356	0.214
Cropping system × cropping season	1, 4	1.875	0.243	0.319

Note: Degrees of freedom (df) are reported as numerator and denominator values. Partial η^2 indicates effect size. Analyses were conducted using field-level means, with each field treated as an independent experimental unit (n: 6). Because the within-subject factor contained two levels, the assumption of sphericity was automatically satisfied. Therefore, Greenhouse-Geisser and Huynh-Feldt corrections produced identical results

Table 4. Paired samples t-test comparing Shannon-Wiener diversity index (H') between monoculture and polyculture systems within each cropping season

Cropping season	Mean difference (Mono-Poly)	SE	95% CI	t	df	p	Cohen's D
Season 1	-0.328	0.074	-0.480 to -0.177	-4.41	2	<0.001	-0.735
Season 2	-0.150	0.114	-0.382 to 0.079	-1.33	2	0.191	-0.222

Note: Mean difference represents monoculture minus polyculture values. Values are based on paired comparisons at the field level (n: 3 pairs; df: 2). CI: confidence interval; Cohen's d indicates the standardized effect size

Differences between cropping systems within each season on dominance (D)

Differences in Simpson's dominance index (D) between cropping systems were also examined using paired samples t-tests (Table 6). During the first cropping season, dominance did not differ significantly between monoculture and polyculture systems (t(2): 0.92, p: 0.363). The mean difference was 0.023 (95% CI: -0.028 to 0.075), with a small effect size (Cohen's d: 0.154). Similarly, during the second cropping season, no significant difference in dominance was observed between cropping systems (t(2): 0.71, p: 0.481). The mean difference was 0.023 (95% CI: -0.042 to 0.088), and the effect size was also small (Cohen's d: 0.119).

Natural enemy-to-pest ratio (NE:P) dynamics

The functional composition of arthropod communities varied between cropping systems and across seasons, as illustrated in Figure 4. Total arthropod abundance, calculated as the cumulative number of individuals recorded from weekly observations across all sampling units within each cropping system, was slightly higher in the monoculture system (884 individuals in Season 1 and 914 individuals in Season 2) than in the polyculture system (781 and 796 individuals, respectively). Despite the higher overall abundance in monoculture fields, the functional composition of arthropods differed markedly between systems. Pest abundance was consistently greater in monoculture (317 and 287 individuals in Seasons 1 and 2, respectively) compared with polyculture (217 and 226 individuals). In contrast, predator abundance was higher in polyculture (349 and 339 individuals) than in monoculture (286 and 308 individuals). A similar pattern was observed for parasitoids. Egg parasitoids were more numerous in polyculture (16 and 15 individuals) than in monoculture (4 and 3 individuals), while other parasitoid groups showed comparable or slightly higher abundance in polyculture across both seasons.

When predators and parasitoids were grouped as Natural Enemies (NE), clear differences emerged in their relative abundance compared with pest populations. Polyculture systems exhibited consistently higher natural enemy-to-pest ratios than monoculture systems (Table 7). In Season 1, the pooled NE:P ratio reached 1.90 in polyculture compared with 1.17 in monoculture. Similarly, in Season 2, the ratio was 1.82 in polyculture and 1.28 in monoculture. These pooled totals indicate a higher relative abundance of natural enemies in the polyculture system.

Because pooled totals may obscure variability among sampling fields, natural enemy dominance was further evaluated using field-level proportions. For each field, seasonal totals of natural enemies and pest individuals were first calculated by summing weekly observations, and the proportion of natural enemies was then expressed as NE/(NE+P). Mean values and standard errors were subsequently calculated across fields within each cropping system. Across both cropping seasons, the mean proportion of natural enemies relative to pests tended to be higher in polyculture fields than in monoculture fields (Table 8).

In addition to natural enemies and pests, other functional groups also displayed system-dependent patterns. Herbivores and vectors were more frequently recorded in monoculture fields, particularly during Season 2. Aquatic decomposers and pollinators were observed only in polyculture systems, whereas detritivores were markedly more abundant in monoculture fields, especially in Season 2. Decomposer abundance was relatively comparable between cropping systems. Overall, although monoculture fields supported slightly higher total arthropod abundance, polyculture systems consistently showed a higher relative representation of natural enemies than pests, suggesting a more balanced trophic structure and greater potential for natural biological control.

Table 5. Paired samples t-test comparing Pielou's evenness index (E) between monoculture and polyculture systems within each cropping season

Cropping season	Mean difference (Mono-Poly)	SE	95% CI	t	df	p	Cohen's D
Season 1	-0.013	0.021	-0.055 to 0.030	-0.61	2	0.544	-0.102
Season 2	0.055	0.114	-0.007 to 0.118	-1.80	2	0.081	0.299

Note: Mean difference represents monoculture minus polyculture values. Values are based on paired comparisons at the field level (n: 3 pairs; df: 2). CI: confidence interval; Cohen's d indicates the standardized effect size

Table 6. Paired samples t-test comparing Simpson's dominance index (D) between monoculture and polyculture systems within each cropping season

Cropping season	Mean difference (Mono-Poly)	SE	95% CI	t	df	p	Cohen's D
Season 1	0.023	0.025	-0.028 to 0.075	0.92	2	0.363	0.154
Season 2	0.023	0.032	-0.042 to 0.088	0.71	2	0.481	0.119

Note: Mean difference represents monoculture minus polyculture values. Values are based on paired comparisons at the field level (n: 3 pairs; df: 2). CI: confidence interval; Cohen's d indicates the standardized effect size

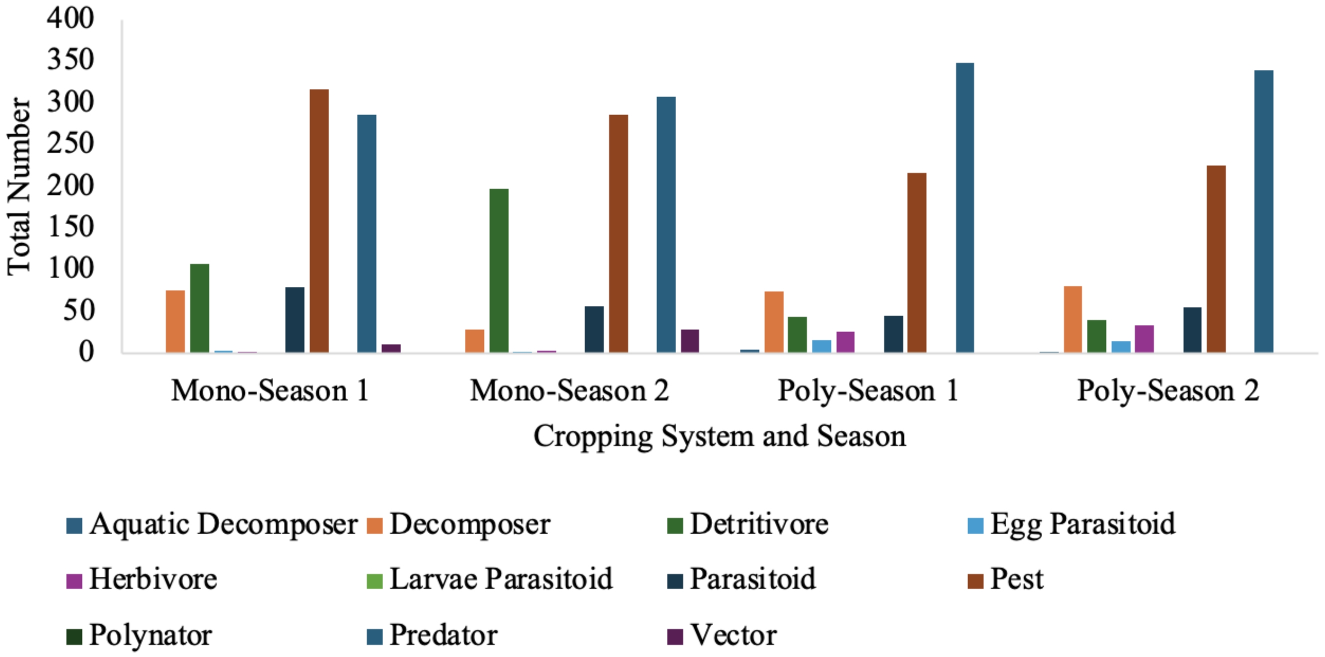

Figure 4. The distribution of arthropod functional roles varies between cropping systems and across seasons

Table 7. Seasonal totals of arthropod functional groups and pooled natural enemy-to-pest ratios (NE:P) across cropping systems

Cropping system	Season	Total individuals	Natural enemies (NE)	Pest (P)	NE:P ratio
Monoculture	1	884	370	317	1.17
Monoculture	2	914	368	287	1.28
Polyculture	1	781	412	217	1.90
Polyculture	2	796	411	226	1.82

Note: Values represent pooled totals across all sampling weeks and sampling units within each cropping system. Natural enemies (NE) include predators and parasitoids. The NE:P ratio represents the abundance of natural enemies divided by the abundance of herbivorous pests

Table 8. Field-level comparison of natural enemy proportions (NE/(NE+P)) between cropping systems

Cropping season	Cropping system	Mean NE/(NE+P)	SE	n (fields)
Season 1	Monoculture	0.539	0.078	3
	Polyculture	0.655	0.038	3
Season 2	Monoculture	0.562	0.112	3
	Polyculture	0.645	0.014	3

Note: Proportions were calculated for each field using seasonal totals of natural enemies (NE) and pest individuals (P). Values represent mean proportions across fields within each cropping system (n: 3 fields per system)

Discussion

The temporal increase in diversity (H′) and evenness (E) from early to mid-season, followed by a decline toward crop maturity, likely reflects successional dynamics commonly observed in annual agroecosystems. During early crop establishment, habitat structure and resource heterogeneity remain limited, potentially constraining niche availability and trophic complexity. As the rice canopy develops, increasing structural complexity can create additional microhabitats, refuge spaces, and prey resources that facilitate species coexistence and reduce competitive exclusion (Fornoff et al. 2021; Lucatero et al. 2024). This structural development provides a plausible explanation for the mid-season peak in diversity observed across fields. However, because vegetation structure and microclimatic conditions were not directly quantified in this study, these mechanisms should be interpreted as ecologically plausible rather than as direct causal evidence.

The inverse pattern observed for dominance (D) is also consistent with processes of community stabilization during crop development. High dominance during early crop stages may result from rapid colonization by a limited number of opportunistic species adapted to disturbed or simplified habitats (Achury et al. 2020). As the system develops, increasing interspecific interactions, including predation, parasitism, and resource partitioning, may limit monopolization by dominant taxa, resulting in reduced dominance and greater evenness (Hood et al. 2021). The subsequent increase in dominance toward crop maturity may reflect habitat simplification associated with crop senescence and declining resource availability (Spiesman et al. 2020). Similar temporal shifts have been reported in other rice agroecosystems, where arthropod communities track changes in crop phenology and habitat structure.

Seasonal variation played a measurable role in shaping certain aspects of community structure, particularly evenness. The significant effect of cropping season on E suggests that temporal environmental variation contributed substantially to differences in the distribution of species abundances. Differences between cropping seasons may reflect climatic variability, crop growth performance, or broader landscape context that influence arthropod colonization and persistence. Temperature and humidity, for example, are known to affect arthropod reproduction, dispersal capacity, and trophic interactions (Tougeron et al. 2020; Fischer et al. 2022). Because these environmental variables were not explicitly measured, the seasonal patterns observed here likely represent context-dependent ecological responses rather than fixed effects of cropping systems. Future studies incorporating microclimatic monitoring and landscape-level variables help clarify these drivers.

In contrast to seasonal effects on evenness, the cropping system had a strong influence on overall diversity (H′), indicating that differences between monoculture and polyculture were expressed primarily through changes in species diversity rather than uniform shifts across all community metrics. The higher diversity observed in polyculture, particularly during the first cropping season, is consistent with the habitat heterogeneity hypothesis, which proposes that increased plant diversity expands niche dimensionality and trophic pathways for arthropods (Farooq et al. 2022; Rakotomalala et al. 2023). In this study, diversification was achieved primarily through vegetation on bunds and field margins, which may provide floral resources, alternative prey, or microclimatic buffering, thereby supporting more complex arthropod assemblages (Creze and Horwath 2021; Hawes et al. 2021).

Nevertheless, the absence of consistent diversity differences across both seasons highlights the context-dependent nature of diversification effects. Climatic variability, differences in crop growth conditions, or fluctuations in pest populations may mediate the strength of biodiversity responses (Mihrete and Mihretu 2025). This variability aligns with recent meta-analyses demonstrating that the outcomes of diversification practices often depend on local biodiversity baselines and landscape simplification (Sánchez et al. 2022). Therefore, while polyculture was associated with higher diversity under certain conditions, its effects were not uniform across temporal contexts.

The lack of statistically significant differences in evenness between cropping systems further suggests that abundance distributions may be shaped more strongly by temporal resource dynamics than by cropping configuration alone. Even within diversified systems, dominance patterns may persist if particular taxa can exploit key resources more efficiently (Menta and Remelli 2020). Similarly, the absence of a statistically significant effect of cropping system on dominance, despite a relatively large effect size, indicates that differences in dominance may exist but were not consistently expressed across fields. This pattern suggests that crop diversification may influence species richness or diversity without necessarily altering the structure of abundance distributions predictably. Such findings emphasize the importance of considering multiple community metrics when evaluating biodiversity responses to agroecological management.

Observed patterns in functional composition provide additional insight into how cropping systems may influence ecological processes. Polyculture fields tended to support higher relative proportions of natural enemies compared to pest populations, indicating a shift in trophic structure. These patterns are broadly consistent with the enemy's hypothesis, which proposes that diversified vegetation can enhance natural enemy abundance by providing alternative prey, nectar resources, or shelter (Blassioli-Moraes et al. 2022; Josephrajkumar et al. 2022). However, because plant species composition, floral resource availability, and natural enemy behavior were not directly measured, these mechanisms should be interpreted as potential ecological explanations rather than confirmed causal pathways. Additional studies quantifying resource availability and predator-prey interactions would be required to verify these mechanisms.

Although monoculture fields exhibited slightly higher total arthropod abundance, this did not correspond to greater potential for biological regulation. Instead, higher pest abundance in monoculture may reflect resource concentration effects, in which simplified crop habitats facilitate host location and the persistence of specialist herbivores (Wenda-Piesik and Piesik 2020; Andow 2023). In contrast, vegetation associated with polyculture systems may interfere with pest host-finding efficiency while simultaneously supporting natural enemy recruitment (Wan et al. 2022). However, because pesticide use and other agronomic inputs were managed independently by farmers and were not quantitatively documented, management differences among fields may also have contributed to the observed patterns.

Patterns in the relative abundance of natural enemies further highlight the importance of functional community composition. Ecosystem services such as biological pest regulation are influenced not only by total arthropod abundance but also by the proportional representation of functional groups within the community (Le Provost et al. 2023). A higher relative abundance of predators and parasitoids in polyculture fields indicates greater potential for ecological resilience and pest suppression. At the same time, the relatively consistent seasonal patterns in natural enemy-to-pest ratios suggest that climatic drivers may also influence trophic balance. Temperature-dependent metabolic rates and phenological synchrony between pests and their natural enemies can affect the strength and timing of trophic interactions (Ramos-Aguila et al. 2023).

Some aspects of functional guild classification also warrant clarification. The category "vector" refers to arthropods that may act as potential vectors of plant pathogens, particularly sap-feeding insects capable of transmitting diseases in rice systems (Lefèvre et al. 2022). Likewise, the designation of "pollinators" includes arthropod taxa commonly recognized as flower visitors in agricultural landscapes (Duque-Trujillo et al. 2023). Although rice is primarily wind-pollinated, flowering plants on bunds or in surrounding vegetation may attract pollinating insects captured during sampling. Because these functional roles were assigned based on ecological literature rather than direct behavioral observations, the guild classification should be interpreted as indicative rather than definitive.

Several limitations should be acknowledged when interpreting these findings. First, the number of field replicates was relatively small, which may limit statistical power and the generalizability of results. Second, the study was conducted in independently managed farmer fields, and although general agronomic practices were broadly comparable, detailed information on pesticide applications, fertilization regimes, and other inputs was not systematically recorded. Such variability may introduce confounding effects in comparisons between cropping systems (Staton et al. 2021; Litovska et al. 2025). Third, this study inferred potential biological control from community composition rather than directly measuring predation or parasitism rates. Future studies incorporating standardized management records, more field replicates, and direct measurements of trophic interactions would provide stronger inference into the mechanisms underlying arthropod community dynamics.

In conclusion, this study highlights the importance of temporal dynamics and cropping system configuration in shaping arthropod communities in rice agroecosystems. Arthropod diversity increased under polyculture compared with monoculture, though this effect was not consistently observed across seasons. Evenness was more strongly influenced by seasonal variation, indicating that temporal environmental conditions play a key role in structuring abundance distributions. Dominance patterns showed no statistically significant response to cropping system or season, although some tendencies suggest potential differences warranting further investigation. Polyculture fields were associated with higher relative proportions of natural enemies, suggesting a shift in trophic structure rather than uniform increases in overall diversity. These findings indicate that crop diversification through bund and margin vegetation may contribute to ecological functioning primarily by influencing community composition and trophic balance. However, because environmental variables, farm management practices, and trophic interaction rates were not directly quantified, these interpretations should be considered indicative rather than definitive.

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