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Cropping systems and field margin vegetation shape hoverfly-mediated control of bean aphids in smallholder farming systems

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HIGHLIGHTS

- Maize–bean intercrops had fewer aphids and more hoverflies compared to monocropped beans.
- Diverse floral field margins increase hoverfly larvae and adults compared to homogenous margins.
- Hoverfly larval abundance negatively correlated with aphid populations.
- Habitat diversification enhanced hoverfly-mediated biological control of bean aphids.

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ABSTRACT

Hoverflies (Syrphidae) are important biological control agents in agriculture because their larvae prey on soft bodied insects such as aphids, while adults also contribute to crop pollination. In many smallholder farming areas, the prevalent hoverfly species are not well-described, nor are the factors associated with their population dynamics and potential role in aphid suppression understood. Here we aimed to identify aphidophagous hoverfly species in maize-bean intercrops and bean monocrop fields, assessing the influence of field margin floral diversity on hoverfly and bean aphid abundance in two districts of Malawi. The study was conducted across 330 farmer managed bean fields in Lilongwe and Salima Districts. Aphid incidence and abundance were assessed through systematic visual inspection of randomly selected bean plants, while hoverfly larvae were sampled from aphid-infested plants and adults were collected using sweep netting in the observational field. A total of 760 hoverflies belonging to eight species were collected, with five being predatory. Data analysis showed that district, bean cropping system, field margin floral diversity and bean growth stage significantly affected both aphid incidence and abundance. Maize-bean intercropping was significantly associated with lower bean aphid incidence and abundance compared with monocropped bean fields. Fields with high field margin floral diversity showed lower aphid incidence and abundance than those with low floral diversity. The flowering bean stage was associated with both high aphid incidence and abundance. Hoverfly larvae and adult populations were highest in Lilongwe District compared with Salima District and in fields with high field margin floral diversity. Hoverfly larvae and adults were significantly more abundant in maize-bean intercrops than in bean monocrop fields and both life stages recorded highest abundance during the flowering bean stage. This study shows that hoverfly abundance was negatively correlated with aphid incidence and abundance in smallholder production systems. Maize-bean intercropping, combined with diverse flowering field margin vegetation was linked to lower aphid populations through enhanced hoverfly presence. Incorporating locally available flowering plants into field margins is a practical, low-input strategy for strengthening natural pest regulation and reducing reliance on synthetic pesticides.

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Introduction

Hoverflies are recognised as beneficial insects in agricultural ecosystems because adults contribute to pollination (van Rijn & Wäckers, 2016), while the larvae of several species act as natural enemies of soft-bodied insects such as aphids (Rotheray & Gilbert, 2011; Leman et al., 2023). Given these ecological roles, hoverflies are particularly relevant in legume-based cropping systems where insect pests pose major production constraints. Across sub-Saharan Africa, beans are one of the most widely grown legumes, but their production is frequently constrained by high pest pressure, especially bean aphids (*Aphis fabae*) (Abate & Ampofo, 1996; Kayange et al., 2019; Ndakidemi et al., 2021), leading to heavy reliance on synthetic pesticides (Laizer et al., 2019; Ngoya et al., 2023). However, the widespread use of chemical pesticides raises concerns about human health and arthropod diversity (Moshi & Matoju, 2017; Rice et al., 2007; Zhou et al., 2025). Aphidophagous hoverflies are important contributors to natural pest regulation, and their conservation and integration within agroecological systems have long been advocated as components of sustainable biological control programmes (Ambrosino et al., 2007; Pineda & Marcos-García, 2008; Van Rijn et al., 2013; Jabeen et al., 2026; Jiang & Wu, 2026). Several studies have reported that hoverflies are among the most abundant predators of aphids in common bean (*Phaseolus vulgaris*) (Abro et al., 2019; Almohamad et al., 2009; Pekas et al., 2020; Woolley et al., 2022). For smallholder farmers in Malawi, beans are an important source of food security and income (Chitete et al., 2023) and contribute to soil fertility through nitrogen fixation (Snapp et al., 1998). By suppressing aphid populations in bean cropping systems, hoverflies can reduce pest-induced yield losses and consequently decrease the need for repeated insecticide application, offering a promising option for lowering pesticide reliance while maintaining crop productivity (Abro et al., 2019; Li et al., 2023). One approach to enhance hoverfly-mediated pest control is through habitat manipulation to ecologically engineer agricultural landscapes (Mwani et al., 2021; Ndakidemi et al., 2021). Hoverfly abundance and ecosystem services delivery are strongly influenced by habitat structure, as both cropping system diversity and field margin vegetation determine the availability of floral resources, refugia and suitable conditions for adult survival and larval development (Hogg et al., 2011; Laubertie et al., 2012; Földesi & Kovács-Hostyánszki, 2014). Given this ecological interaction, relationships among hoverfly abundance, aphid population and field margin floral diversity are biologically meaningful. Hoverfly larvae are expected to be negatively associated with aphid abundance due to their predatory role, while field margin floral diversity is expected to positively influence hoverfly populations by enhancing nectar and pollen availability for adults, which may indirectly affect larval populations in crop fields.

For smallholder communities, simple practices like maintaining flowering plants along bean field margins could benefit pest regulation and consequently crop yield stability (Arnold et al., 2021; Ndakidemi et al., 2022a; Ochieng et al., 2022). Although the ecological significance of hoverflies is widely acknowledged (Rodríguez-Gasol et al., 2020; Doyle et al., 2020), most existing research has been conducted in temperate agricultural systems, with limited studies focusing on tropical smallholder landscapes, for example, (Doyle et al., 2020; Montoya et al., 2021; Salat-Moltó et al., 2023; Mansier and Van Rijn, 2024; Roy et al., 2025). In these systems, flowering field margins and diversified cropping landscapes have been shown to increase hoverfly abundance and species richness by providing essential floral resources and complementary habitats that support both pest suppression and pollination services.

Similarly, studies in temperate regions have demonstrated that field margin vegetation composition and structural complexity influence aphid population and their natural enemies including hoverflies (Santos et al., 2018; Schirmel et al., 2018; Wojciechowicz-Żytko and Wilk, 2023). In sub-Saharan Africa, emerging evidence suggests that habitat manipulation can also support hoverfly communities. For example, flowering plant species have been shown to increase hoverfly abundance in Tanzanian bean systems (Ndakidemi et al., 2022b). In an on-station trial in Malawi, flowering plant species established within bean fields enhanced hoverfly species richness and abundance, resulting in reduced aphid damage and improved yield compared with bare margins (Kaliwo et al., 2026).

Research in SSA remains limited, focusing mainly on hoverfly abundance to specific crops or field margins, with less attention given to community composition and functional diversity. Consequently, there is still limited understanding of how cropping systems and field margin floral diversity influence hoverfly species composition in smallholder farms (Gurr et al., 2017; Kabota et al., 2025). This knowledge gap limits the development of locally adapted biological control strategies. Understanding species composition is critical because different hoverfly species vary in their ecological traits and pest control potential.

Based on previous studies showing that intercropping systems can enhance aphid reduction (Wosula et al., 2017) and increase natural enemy abundance (Mwani et al,2021) and that flowering field margins support hoverfly populations by providing essential resources, we expected these habitat features to positively influence hoverfly communities. Evidence suggest that these previous studies have largely concentrated on quantifying hoverfly abundance with little attention to the identification of dominant hoverfly species in smallholder farming systems where some species may not be predatory (Doyle et al., 2020; Montoya et al., 2021; Power et al., 2016; Woolley et al., 2022).

Thus, this study aimed to examine hoverfly diversity and abundance of aphidophagous hoverflies in maize-bean intercrops and bean monocrop fields under contrasting field margin vegetation conditions across two agroecological zones in central Malawi, focusing on cropping system diversity (maize-bean intercrop vs. bean monocrop) and field margin floral diversity as key habitat manipulation factors. Specifically, the study addressed the following research questions: (i) does cropping system (maize-bean intercrop vs. bean monocrop) influence hoverfly abundance and species diversity, (ii) do field margins with diverse floral resources enhance the abundance of aphidophagous hoverflies and (iii) do these patterns differ between agroecological zones in Central Malawi? We hypothesised that maize-bean intercrops and fields with diverse field margin floral diversity would support higher hoverfly abundance and diversity than monocrop systems and fields with low or no field margin floral diversity.

Materials and Methods

Farmer field sites

Hoverfly surveys were conducted in Malawi during the bean cropping season from 10 May to 12 August 2021. The study focused specifically on hoverflies as the target taxonomic group of ecological interest, while field margin floral diversity was assessed as an explanatory habitat variable influencing hoverfly abundance and diversity. Other insect taxa encountered during fieldwork were recorded only opportunistically and were not included in the analysis. The surveys took place in farmer-managed bean fields in Lilongwe and Salima Districts (Fig. 1), which are located in two distinct agro-ecological zones. Both zones are characterized by two seasons (dry, cool season from April to October and hot, wet season from November to March). Lilongwe is in a mid-altitude agro-ecological zone and Salima is in a low altitude agro-ecological zone. Lilongwe (13°58′ S and 33°47′, altitude 1000 to 3400 m above sea level) has a mean annual temperature of 20.4°C and a mean annual rainfall of 739 mm. Salima (13.77°S and 34.45°E, altitude 500 to 1000 m above sea level) has a mean annual temperature of 24°C and a mean annual rainfall of 489 mm (Mupangwa et al., 2023).

A purposive sampling method was used to select six out of nineteen extension planning areas (EPA) in Lilongwe (Thawale, Mlomba, Chitsime, Mitundu, Mkwinda, and Malingunde) and five out of seven EPAs in Salima (Chipoka, Chiluwa, Tebwe, Katerela, and Matenje). In Malawi,

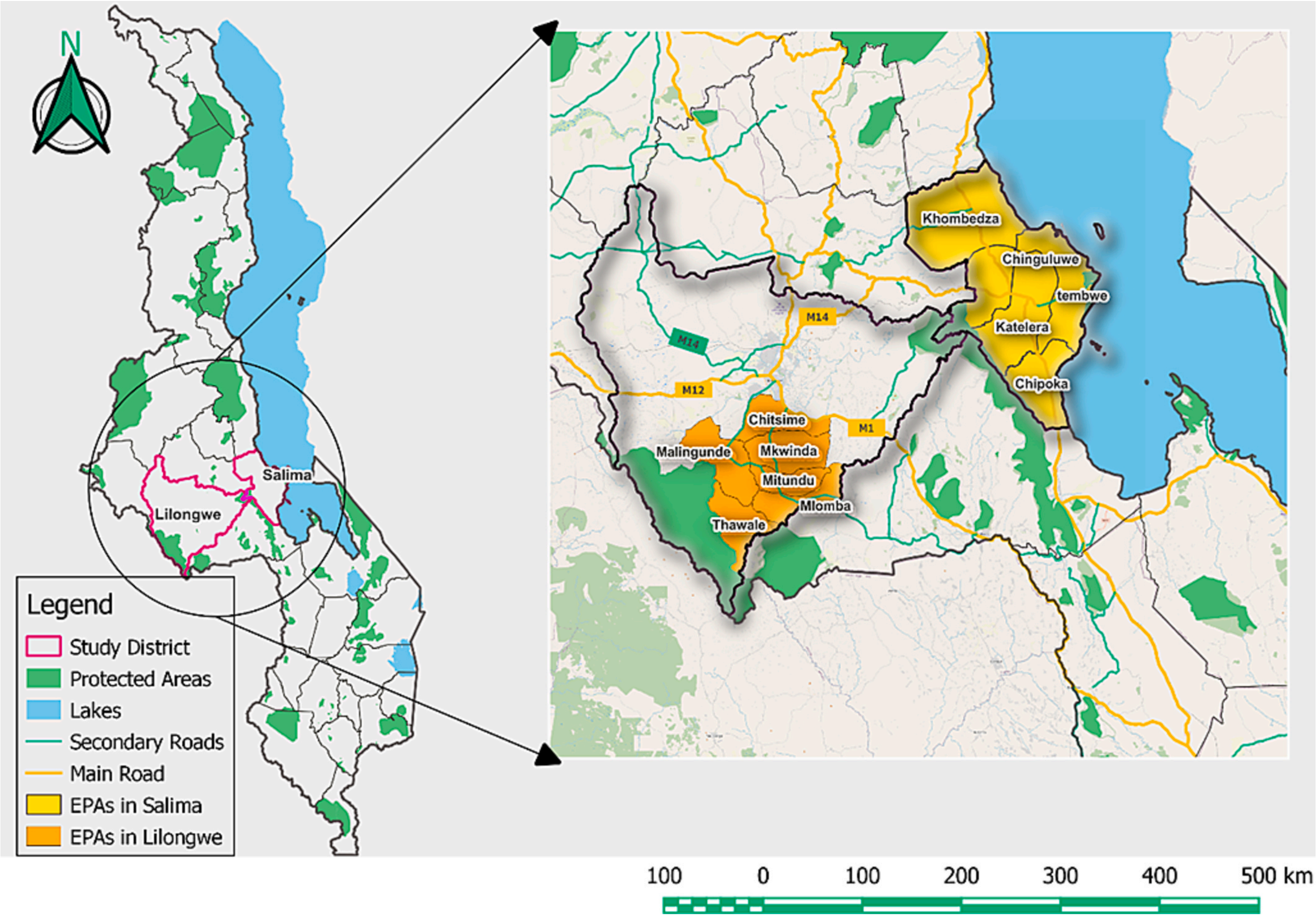


Fig. 1. Map study locations in Malawi indicating the regions of Lilongwe and Salima Districts.

EPAs are administrative zones used by agricultural extension systems that organise and deliver services to farmers at the community level. Purposive sampling is a non-random sampling method in which study elements are selected intentionally based on the specific characteristics or criteria relevant to the objective of the research (Etikan et al., 2016).

Within each EPA, thirty aphid-infested smallholder fields were selected for aphid scouting and hoverfly collection, resulting in a total of 330 fields across the two districts. Although farmer-managed fields varied in size (approximately 0.5–1.5 ha), all biological data collection was standardised using a fixed 10 m x 10 m sampling plot established within each field. Within each field, a hierarchical sampling design was applied. First, a single representative field margin was selected based on accessibility, continuity and the vegetation structure. The 10 m x 10 m insect sampling plot was established adjacent to the selected margin to ensure direct ecological correspondence between plant and insect sampling units.

Each field was surveyed once during the study period. Insect sampling was conducted between 08:00 and 12:00 h during warm, calm weather conditions and windy periods were avoided to minimise effects of insect activities and detectability. Time of the day and weather conditions (temperature, wind light and humidity) are known to strongly influence insect activity, thus a standard protocol was employed to restrict the survey to a time with favourable weather (Grange et al., 2021; Mahon and Hodge, 2022). Approximately six fields were sampled per day, resulting in a total of 55 sampling days across all EPAs.

Both bean monocrop and maize-bean intercrop fields were encountered across multiple EPAs in both Lilongwe and Salima. Intercropping was consistent across sites and consisted of within-row maize-bean intercropping, with beans planted between maize stations along the same ridge. Although not experimentally controlled, these field level configurations were recorded for each site. While aphid infestation was the primary selection criterion, the cropping system (monocrop vs intercrop) was documented during field visits and included as a variable in data analysis to assess its potential influence on aphid incidence and hoverfly abundance. The distribution of sampled fields across districts, EPAs, cropping systems, field size and field coordinates and was recorded (Supplementary Table S1 and Table S2).

Distances between sampled fields ranged from approximately 700 m to 1 km, with an average separation distance of approximately 850 m. Although no fixed spacing criterion was imposed during field selection, efforts were made to ensure broad spatial representation within each EPA. The insect scouting and collection were conducted by trained entomology technicians from the Department of Crop and Soil Sciences, LUANAR (three for sweep netting and four for hoverfly larvae and aphid assessments). All personnel had prior experience in insect sampling techniques including sweep netting and visual insect population assessments. Additional standardized training and supervision were provided during initial sampling to ensure consistency across sites.

Aphids and hoverfly sampling

Within each 10 m x 10 m sampling plot, ten bean plants were randomly selected from the ten middle rows using a zigzag pattern for assessments of aphid incidence, aphid abundance and hoverfly larval abundance. Sampling within the middle row minimised within-plot edge effects while maintaining the standardised position of plots adjacent to field margins. The selected plants were visually inspected for presence of *A. fabae*. Aphid incidence was calculated as the percentage of sampled plants infested with aphids within each field and was expressed as the number of infested plants relative to the total number of plants examined multiplied by 100.

Aphid abundance was assessed on the same ten randomly selected plants using an infestation scoring scale of 0–5 where: 0 = no aphid infestation, 1 = a few scattered aphids (1 − 100), 2 = a few isolated colonies (101 − 300), 3 = several isolated colonies (301 − 600), 4 = large isolated colonies (601 − 1000), and 5 = large continuous colonies (>1001) (Mwani et al., 2021). Although aphid infestation was initially recorded using an ordinal 0–5 infestation scoring scale for standardised field assessment, raw aphid counts per plant were also recorded during sampling. The scoring system was used only for field-level standardisation and rapid assessment of infestation intensity. Within these randomly selected plants, those with aphid infestation were further examined for presence and abundance of hoverfly larvae. Larvae encountered were counted, recorded and collected for laboratory rearing and subsequent species identification. These observations formed the basis for all quantitative analyses of aphid and hoverfly larvae abundance. To assess aphid-hoverfly association at plant level, aphid-infested plants within the random sample were first identified. Where fewer than ten infested plants were obtained, additional aphid-infested plants were purposively selected to reach a maximum of ten per field. On these plants, only the presence or absence of hoverfly larvae was recorded, larval counts were not conducted and these plants were excluded from abundance analyses.

Hoverfly larvae collected from randomly selected plants were transported in aerated containers (11 x 14 x 4 cm, ARKY Plastic Industry Ltd., Malawi) to the entomology laboratory at Lilongwe University of Agricultural and Natural Resources. Larvae were maintained at room temperature (25–27°C) and relative humidity of 50–60% and fed daily with live *Aphis fabae* until pupation and adult emergence for species identification. The aphids used for rearing were originally collected from infested bean fields in the study area and subsequently maintained as a laboratory culture on potted bean plants under greenhouse conditions throughout the study period to ensure a continuous food supply.

Sweep net sampling was used to capture adult hoverflies following Spafford & Lortie (2013). Sampling was conducted with a single representative field margin per field, consisting of herbaceous vegetation bordering the bean crop. In each field, sweep netting was carried out using a transect-based approach by walking slowly in a straight line parallel to the field edge at a distance of approximately 0.5 m from the vegetation boundary. At each field visit, 10 standardised sweeps were made over approximately 5 m along the margin transect. The net was swept continuously through vegetation in a consistent arc to ensure comparable sampling effort across fields. Sampling was conducted under calm weather conditions, avoiding rainy and windy periods to minimise variation in insect activity and detectability. Each field was sampled once during the study period, and sampling corresponded to prevailing bean growth stage at the time of field visit (vegetative, flowering and podding stage).

When adult hoverflies were captured, the nets were closed and the insects were transferred to kill jars containing cotton wool soaked in ethyl acetate. Camel brushes were later used to transfer dead hoverflies from the jars to 60 ml bottles containing 70% ethanol (Pineda & Marcos-García, 2008). The insects were identified to species level using several identification keys (Curran, 1938; Pérez-Bañón & Marcos-García, 2000; Chvala, 2006; Mengual, 2018; Ramage et al., 2018; Mengual et al., 2020; Kirk-Spriggs & Sinclair, 2021), with specimens archived at Lilongwe University of Agriculture and Natural Resources. Representative samples of the hoverfly species were sent to the Department of Museums and Monuments of Malawi, where a taxonomist confirmed the identifications.

Flowering plant species

Field margin vegetation was assessed on the same day as insect sampling by a botanist from the National Herbarium and Botanic Gardens of Malawi. Within each field margin two 1 m^2 quadrats were placed adjacent to the insect sampling plot. Quadrat placement was standardized and independent of margin length, with quadrats distributed to capture local variation in vegetation while maintaining direct ecological linkage to the sampling plot. Field margins typically occurred as strips of uncultivated vegetation ranging from approximately 5 to 30 m width along the field boundary however the margin dimensions were not directly measured.

Within each quadrant, all flowering plant species were recorded and counted. Only plants in the flowering stage were included to ensure accurate species identification and to reflect floral resources available to adult hoverflies. Species identification was conducted to species level using standard botanical references, including Germishuizen & Meyer (2003) and Williamson (1975). A complete list of all plant species recorded in the field margin is provided (Supplementary Table S2). Field margin floral resource diversity was quantified as flowering plant species richness derived from two 1 m^2 quadrats per field margin. Field margins were classified into low and high diversity categories using a median split of species richness across all sampled fields. Margins with species richness above the median were classified as high diversity, while those at or below the median were classified as low diversity. All individual flowering plants species within each quadrant were counted and relative abundance was calculated as:

$$\text{Relative abundance of species} = \frac{\text{Number of individuals of a given species}}{\text{Total number of individuals of all species in the quadrat}} {*}100$$

Data analysis

A generalized linear mixed modelling (GLMM) framework was used to analyse aphid and hoverfly responses. Aphid incidence, recorded as presence or absence of aphids across ten randomly selected plants per field, was analysed using a binomial GLMM with a logit link function. Aphid abundance was recorded using an ordinal infestation scale (0–5), representing increasing levels of infestation intensity. Although ordinal in nature, this variable was treated as an ordered abundance index and analysed using a negative binomial GLMM with a log link function to accommodate its count-like structure and potential overdispersion commonly observed in ecological field data. Hoverfly larvae and adult abundance, which were recorded as count data derived directly from field observations, were analysed using negative binomial GLMMs with a log link function to account for overdispersion typical of ecological count datasets, as confirmed through preliminary dispersion diagnostics. For all GLMMs, district, cropping system bean growth stage and field margin diversity were included as fixed effects (independent variables), while EPA was included as a random effect to account for spatial clustering of sampling location. Two-way, three way and four-way interaction terms among district, cropping system, bean growth stage and floral resources diversity were included to assess whether their effects varied across aphid and hoverfly responses. Where significant main effects were detected, post hoc pairwise comparisons were conducted using estimated marginal means (EMMs) with Tukey adjustment for multiple comparisons.

Spearman correlation was used to assess the relationship between aphid abundance and hoverfly larva abundance using data derived exclusively from randomly selected plants included in quantitative abundance assessment. Additional aphid-infested plants that were purposively selected to assess aphid-hoverfly association based on hoverfly larval presence or absence were excluded from abundance analyses. A separate Spearman correlation was used to assess the relationship between adult hoverfly abundance and floral resources diversity in the field margins. The Shannon-Wiener diversity index was used to quantify hoverfly diversity. Data on flowering plant species in field margin vegetation were summarised by district and species were ranked according to their relative frequency of occurrence across sampled fields relative to the total occurrence of flowering plant species. All the statistical analyses were performed using Genstat 21st Edition (VSN International Ltd).

Results

Impact of district, bean cropping system, field margin floral diversity and bean growth stage on aphid incidence and abundance.

District, bean cropping system, bean growth stage and field margin floral diversity had significant effects both on aphid incidence and aphid abundance (Table 1). Aphid incidence was consistently higher in Lilongwe District than in Salima District (Fig. 2), and aphid abundance followed the same trend (Fig. 3). Among the cropping systems, bean monocropping recorded the highest aphid incidence compared with the maize-bean intercrop (Fig. 2), and aphid abundance showed a similar pattern (Fig. 3). Moreover, fields margins characterized by low floral diversity had higher aphid incidence than those with high floral diversity (Fig. 2) and aphid abundance also showed a similar trend (Fig. 3). The bean flowering stage had both the highest aphid incidence and abundance (Figs. 2 and 3). Significant interactions were also observed for aphid responses (Table 1). Aphid incidence was influenced by the interaction between bean growth stage and field margin floral diversity. In addition, the interaction between cropping system and field margin floral diversity significantly affected both aphid incidence and aphid abundance. Non-significant interaction terms are presented in (Supplementary Table S4).

Table 1
Generalized linear mixed model (GLMM) results for aphid incidence, aphid incidence abundance score, hoverfly larvae and adult hoverflies population from bean plots that were surrounded by different flowering plant species in the field margins. Boldface indicates statistically significant effects ($p \leq 0.05$).

Source of variation	DF	Aphid incidence	Aphid score	Hoverfly larvae	Hoverfly adult
District	1				
F		12.99	7.69	10.05	47.02
Pr > F		**0.002**	***0.003***	**0.002**	**0.001**
Bean cropping systems	1				
F		25.89	67.38	5.9	5.60
Pr > F		***0.001***	***<0.001***	***0.002***	***0.019***
Field margin diversity	1				
F		35.59	30.05	18.73	19.79
Pr > F		***0.001***	***0.001***	***0.001***	***0.001***
Bean crop growth stages	3				
F		4.97	12.09	6.81	8.29
Pr > F		*0.002*	<*0.001*	*0.008*	*0.004*
Bean crop growth stages x Field margin vegetation diversity	3				
F		3.90	2.24	0.25	0.18
Pr > F		***0.009***	0.133	0.858	0.913
Bean crop growth stages X Bean cropping systems x District	3				
F		2.70	1.40	0.99	1.99
Pr > F		***0.046***	0.243	0.399	0.115
Bean cropping systems × Field margin diversity	1				
F		7.93	3.19	0.20	0.15
Pr > F		**0.035**	***0.001***	0.658	***0.032***
Hoverfly species					
F					7.06
Pr > F					***0.001***

Impact of district, bean cropping system, field margin floral diversity and bean growth stage on hoverfly larvae and adult populations.

District had a significant effect on hoverfly abundance at both larval and adult stages (Table 1). Hoverfly larvae and adults were more abundant in bean fields in Lilongwe compared with those in Salima (Fig. 4). Hoverfly abundance also differed significantly between cropping systems, with higher abundance in maize-bean intercrops than in bean monocrops (Fig. 4). Furthermore, hoverfly larval and adult populations differed significantly between field margins with high and low floral diversity (Table 1). Higher hoverfly abundance was recorded in bean field margins with high floral diversity compared with those with low floral diversity (Fig. 4). Bean growth stages also had a significant effect and differed for both hoverfly larval and adult abundance, with the flowering stage recording highest abundance for both hoverfly larvae and adults (Fig. 4). A significant interaction between cropping system and field margin floral diversity was detected for adult hoverfly abundance (Table 1), whereas other interaction effects were not significant (Supplementary Table S4).

Relationships between the populations of hoverflies, aphids and field margin diversity.

A moderate and statistically significant negative correlation was observed between the hoverfly larvae population and aphid abundance (Table 2). A strong and statistically significant positive correlation was found between the hoverfly population and field margin floral diversity (Table 2). A total of 760 hoverflies representing eight taxa were collected during the survey period (Fig. 5), derived from sweep net sampling of adult hoverflies in the field and from adults reared from field collected larvae. Species identification revealed five taxa classified as aphidophagous at larval stage based on published Syrphidae ecological literature (*Ischiodon aegyptius, Toxomerus floralis, Allobaccha curran, Betasyrphus adligatus and Asarkina* sp.*)*, while the remaining taxa were classified as non-aphidophagous (*Melanostoma* sp.*, Syritta flaviventris* and *Phytomia* sp.) (Fig. 5). Hoverfly species composition differed significantly between Lilongwe and Salima Districts ($p < 0.001$) (Table 1). More hoverflies were caught in Lilongwe than in Salima. Species richness, diversity and evenness were also higher in Lilongwe than Salima (Table 3). *Ischiodon aegyptius* was the most abundant species in both districts, whereas *Phytomia* sp. was the least abundant (Fig. 6). The following taxa: *Asarkina* sp., *Melanostoma* sp. and *Phytomia* sp. were only identified to genus level due to limitations in morphological resolution of field-collected specimens, including ambiguous diagnostic characters required for reliable species level identification under standard Syrphidae keys. Furthermore, Lilongwe District recorded higher species richness number, diversity and evenness compared with Salima (Table 3). On the field margin floral diversity, a total of 13 common flowering plant species were identified in the two districts (Fig. 7). Among these *Ageratum conyzoides* and *Bidens pilosa* were more abundant in Lilongwe District, whereas *Commelina benghalensis* and *Cynodon dactylon* were more abundant in Salima District (Fig. 7).

Discussion

This study demonstrates that maize-bean intercropping is associated with reduced bean aphid incidence and abundance compared with monocropped beans. This finding aligns with previous studies showing that crop diversification disrupts host-finding behaviour in aphids and reduces colonisation success (Sammama et al., 2023; Wosula et al., 2017). It further extends this evidence to smallholder farming systems in sub-Saharan Africa, where field-level heterogeneity may amplify these effects. Intercropped maize may interfere with aphid host detection by inducing non-host landings and delay colonisation (Grauby et al., 2022), while also modifying within-canopy microclimatic conditions in ways that can enhance the foraging efficiency and survivorship of natural enemies (Mkenda et al., 2019; Pierre et al., 2023). Together, these mechanisms provide a plausible explanation for the reduced aphid pressure observed in the intercrop fields in the present study.

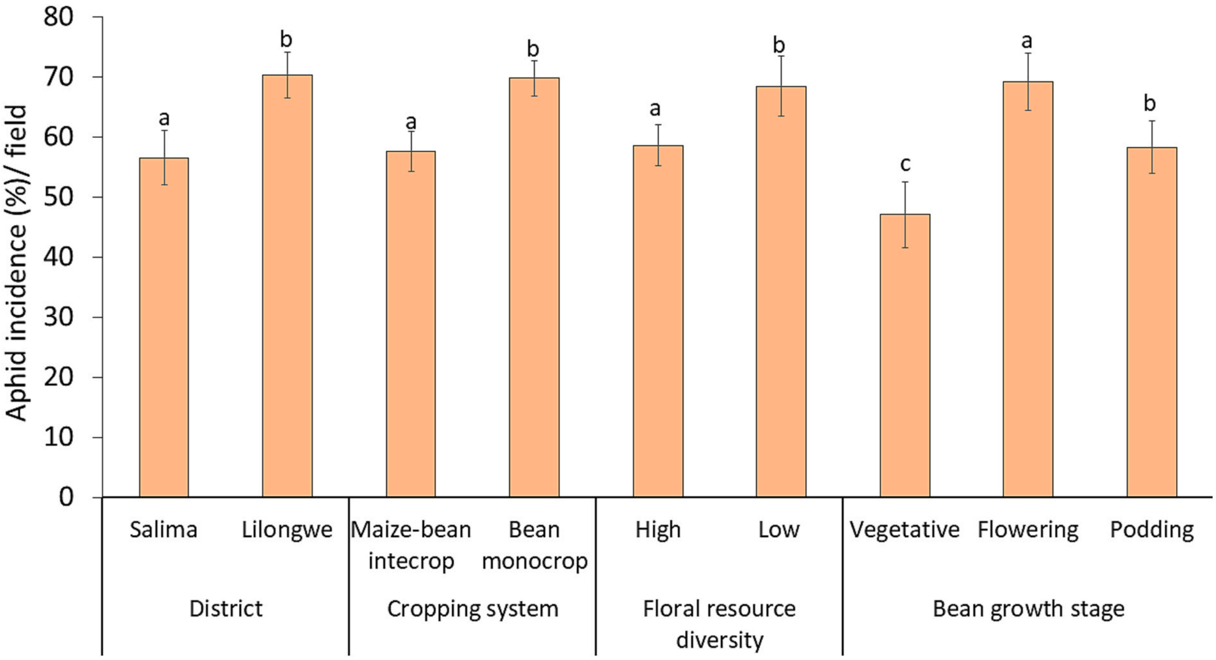


Fig. 2. Effects of district, cropping system, floral diversity and bean growth stage on aphid incidence. Error bars show standard error (SE). Different letters indicate significant differences among treatments (Fisher's LSD, $p < 0.05$).

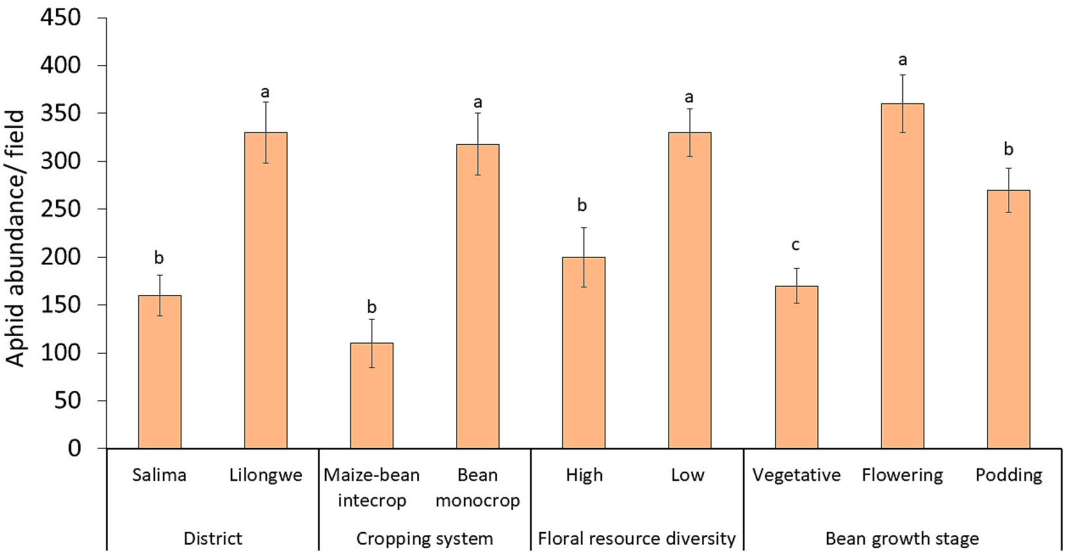


Fig. 3. Effects of district, cropping system, floral diversity and bean growth stage on aphid abundance. Error bars show standard error (SE). Different letters indicate significant differences among treatments (Fisher's LSD, $p < 0.05$).

Our results show that hoverflies were more abundant in maize-bean intercropped fields than in the bean monocropped fields, suggesting that crop diversification may enhance ecological conditions favourable to aphidophagous hoverflies (Pierre et al., 2023). This observation is consistent with findings by Ndakidemi et al. (2022a), who reported that diversified cropping systems support higher natural enemy populations through increased habitat complexity and resource continuity. Similarly, Yousefi et al. (2024), demonstrated that structurally complex cropping systems improve prey detection and foraging efficiency by predators.

Our results go beyond these studies by demonstrating a simultaneous increase in predator abundance and reduction in pest incidence within the same system, strengthening the inference that hoverfly-mediated biological control may be operating in these intercrops. Beyond general predator responses, increased hoverfly abundance may be driven by specific ecological mechanisms. Adult hoverflies depend on nectar and pollen as essential energy and reproductive resources, and maize–bean intercrops may enhance the spatial distribution and continuity of these resources, thereby improving adult survival and retention within crop fields (Pinheiro et al., 2015; Moquet et al., 2018). Furthermore, female hoverflies preferentially lay eggs in aphid-rich environments to ensure larval food availability (Abro et al., 2019). Increased structural heterogeneity in intercrops may improve the ability of females to locate aphid patches while also providing refuge and favourable microclimatic conditions that support adult activity. Together, these mechanisms likely contribute to the higher hoverfly abundance observed in intercropped fields.

Bean growth stage influenced both aphid infestation and hoverfly

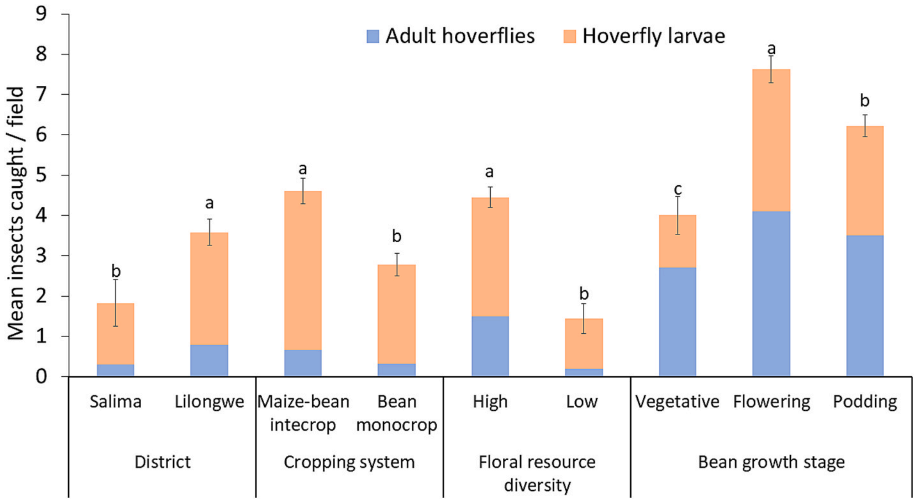


Fig. 4. Effects of district, cropping system, floral diversity and bean growth stage on aphid incidence on hoverfly larval and adult abundance. Error bars show standard error (SE). Different letters indicate significant differences among treatments (Fisher's LSD, $p < 0.05$).

Table 2
Pearson correlation value between the population of hoverfly larvae and aphid abundance.

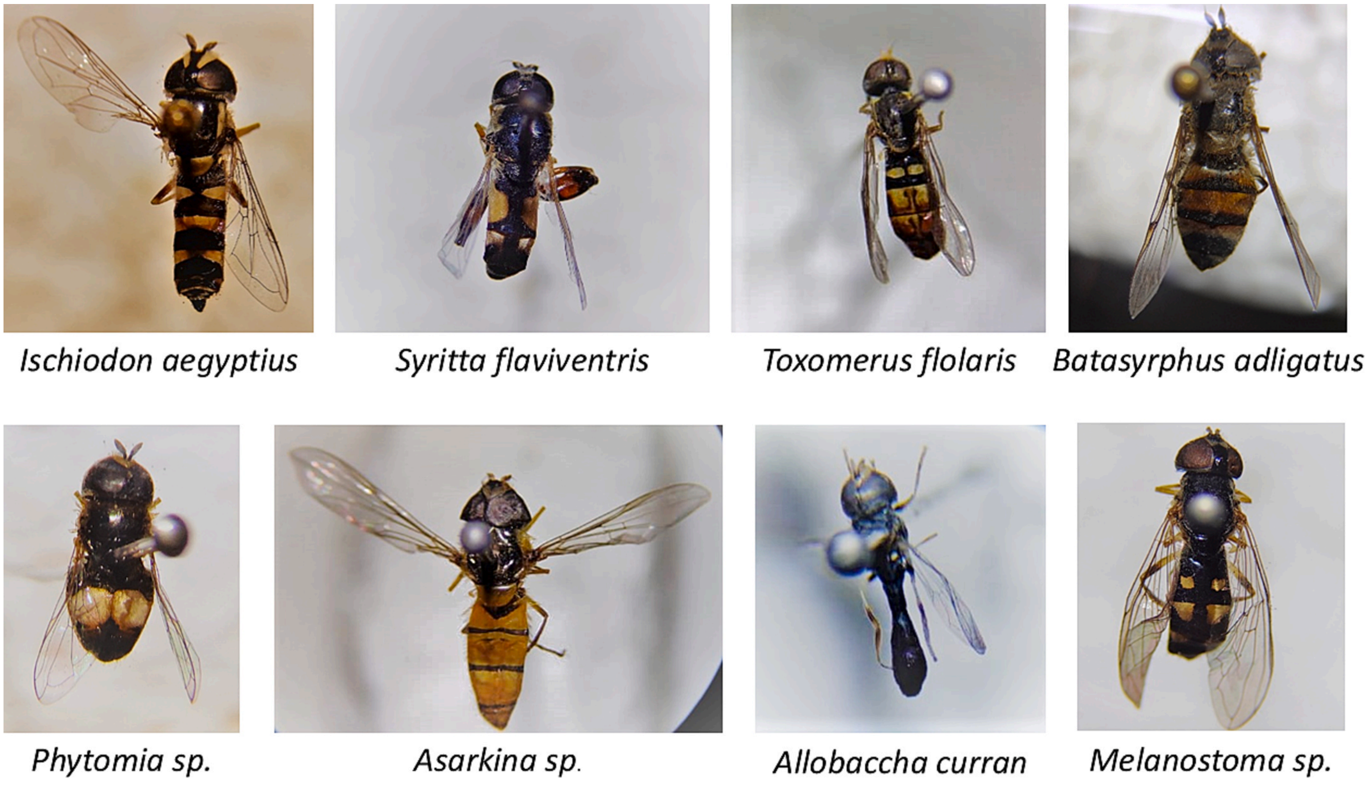
Variables compared	Pearson r
Aphid abundance – Hoverfly larvae	−0.364**
Field floral diversity – Hoverfly pop	0.537**

** indicates significance at *p ≤ 0.01*.

abundance, likely reflecting changes in plant quality and resources availability across phenological stages. The higher aphid pressure observed during the flowering stage may be driven by increased biomass and the availability of young, nutrient rich tissues. Such tissues provide higher quality phloem sap, which enhances aphid feeding efficiency, survival and reproduction (Amin et al., 2020). Similar trends have been reported by Mwani et al. (2021), who observed increasing aphid pressure with advancing bean phenology, suggesting that crop development

Table 3
Hoverfly diversity indices in Lilongwe and Salima Districts.

Diversity indices	Salima	Lilongwe
Species richness (S)	7	8
Evenness (1/D)	4.21	4.81
Diversity (H)	1.64	1.78
Individual hoverfly population	233	527



Ischiodon aegyptius *Syritta flaviventris* *Toxomerus flolaris* *Batasyrphus adligatus*

Phytomia sp. *Asarkina sp.* *Allobaccha curran* *Melanostoma sp.*

Fig. 5. Photos of the hoverfly species captured across Lilongwe and Salima Districts.

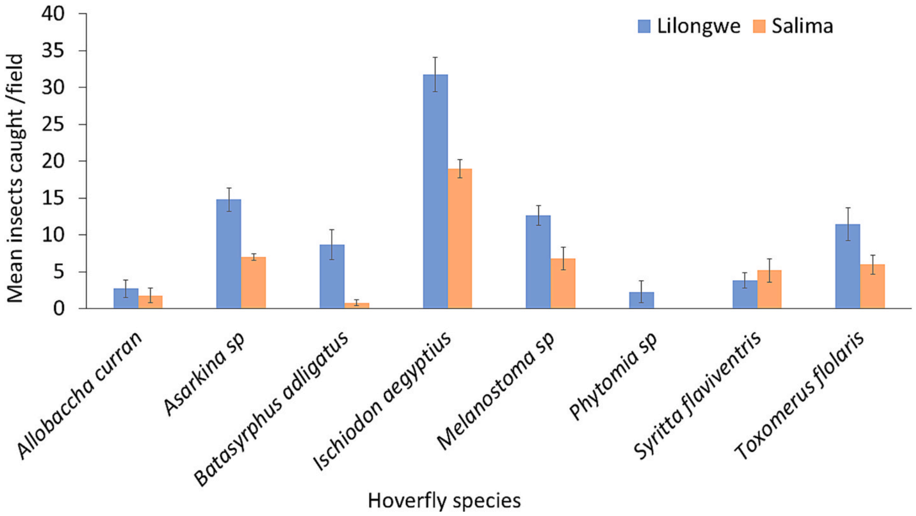


Fig. 6. Mean hoverfly species abundance in Lilongwe and Salima Districts. Error bars represent standard error (SE).

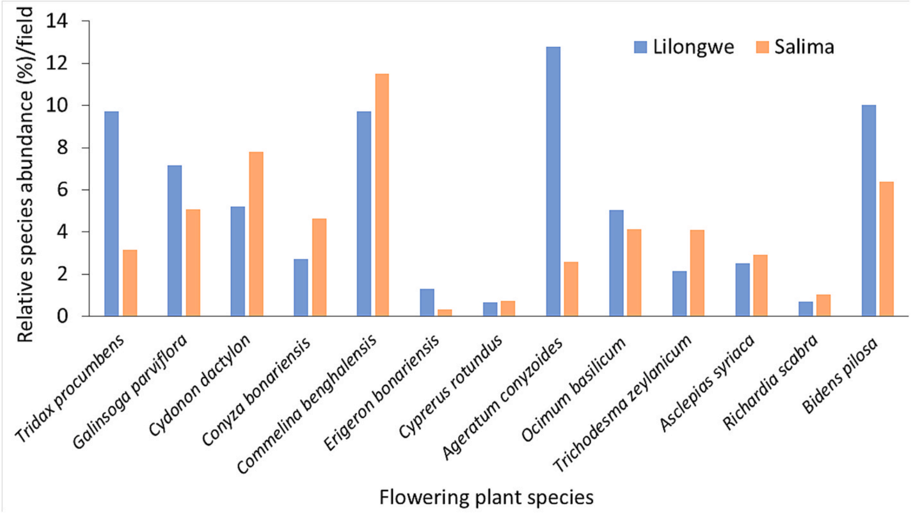


Fig. 7. Common flowering plant species encountered in bean field across Lilongwe and Salima Districts.

stage is a key driver of aphid population dynamics in smallholder farming systems.

The corresponding increase in hoverfly abundance during the flowering stage appears to be driven by both prey and resource mediated mechanisms. In particular, higher aphid densities during flowering likely enhance habitat suitability for aphidophagous hoverflies by increasing oviposition opportunities. Hoverfly females preferentially lay eggs in aphid-rich environments to ensure adequate food resources for their larvae, making aphid abundance a key regulator of hoverfly population establishment (Ramsden et al., 2017; Gonzalez et al., 2024). The observed peak in hoverfly larvae and adults during flowering stages suggests a strong numerical response to increased prey availability consistent with predator prey dynamics commonly reported in agroecosystems. In addition, flowering provides nectar and pollen that support adult hoverfly survival and reproduction. Flowering bean plants provide nectar and pollen, which are essential energy and protein sources for adult hoverflies, thereby supporting survival and reproductive activity. This aligns with findings by Babaei et al. (2018), who reported that floral resource availability with crop fields significantly increases hoverfly visitation and retention. Similarly, Van Rijn & Wäckers, (2016), demonstrated that nectar and pollen availability directly influences hoverfly fecundity and field persistence. Therefore, flowering stage likely creates a dual resources environment, i.e., aphids for larvae and floral resources for adults, which explains the observed peak in hoverfly populations.

Aphid and hoverfly populations were consistently higher in Lilongwe than in Salima, likely reflecting agroecological differences between these zones. Lilongwe generally receives higher rainfall and generally supports higher vegetation biomass, including alternative aphid host plants and diverse flora in crop margins that may provide favourable conditions for aphid and hoverfly reproduction (Moquet et al., 2018). By contrast, the drier, hotter conditions in Salima resulted in sparse vegetation, restricting reproduction and movement of both aphids and hoverflies (Alignier et al., 2014). This pattern is consistent with studies indicating that mid-altitude agroecosystems with higher humidity and vegetation cover tend to support greater aphid population growth and natural enemy activity (Wosula et al., 2017). Furthermore, variations in temperature and relative humidity between the two districts, with a shift from low to mid altitude zones resulting in a decreased mean temperature and increased relative humidity, may create conditions conducive to rapid aphid reproduction and hoverfly performance (Baumann et al., 2021; Sommaggio et al., 2022). Unlike many temperate studies where temperature is the dominant driver, our finding suggests that in smallholder tropical systems, vegetation structure and moisture availability may play a combined role in shaping both pest and natural enemy populations.

Field margin vegetation emerged as an important factor associated with biological control within smallholder bean cropping systems. Bean field margins surrounded by diverse floral resources supported greater hoverfly abundance and lower aphid incidence than those bordered by more homogenous vegetation. These findings strongly support previous work demonstrating that flowering field margins may enhance natural enemy populations by providing essential resources such as nectar, pollen and shelter (Hogg et al., 2011; Kaliwo et al., 2026; Laubertie et al., 2012). However, diverse field margins may also support additional natural enemy communities not quantified here, which could contribute to overall pest suppression.

The strong association between aphid colonies and hoverfly larvae in this study supports known oviposition behaviour where hoverfly females place eggs near aphid aggregations (Abro et al., 2019; Leroy et al., 2010). Early hoverfly oviposition prior to peak aphid build up enables larval emergence during aphid exponential growth, intensifying suppression (Almohamad et al., 2007; Ramsden et al., 2017). Importantly, our results provide field evidence from smallholder systems that margin vegetation not only supports hoverfly presence but is also associated with measurable reduction in pest pressure, reinforcing its functional role in biological control rather than merely serving as habitat. These findings showed that biological control in crop fields may be influenced not only by intercropping but also by margin vegetation, with floral resource availability likely playing a role in shaping hoverfly presence and activity.

The study indicated that *Ischiodon aegyptius* was the most common hoverfly species in both districts. This species is widely distributed and remains active throughout most seasons (Kirk-Spriggs & Sinclair, 2021; Kaliwo et al., 2026). Its dominance in the present study is consistent with reports from other tropical agroecosystems, where generalist and mobile hoverfly species tend to dominate due to their ability to exploit fluctuating prey population. Its short life cycle results in multiple generations each year, enabling it to build up large populations rapidly and effectively prey on large numbers of aphid colonies. The composition of hoverfly communities showed some variations where Lilongwe District displayed higher species richness and composition than Salima District, likely attributed to differences in climate and floristic composition of field margins (Santos et al., 2018) as well as the abundance of aphids. In Lilongwe, the bean field margin vegetation predominantly consisted of Asteraceae such as *Galinsoga parviflora, Bidens pilosa, Ageratum conyzoides*, and *Tridax procumbens*, which hoverflies prefer due to their pollen and nectar production which is suitable for insects with a short proboscis (Klecka et al., 2018). This supports previous findings that plant species with open floral morphology are particularly important in sustaining hoverfly populations in agriculture landscapes. Therefore, our findings provide field-based support from smallholder agroecosystems in Malawi for well-established ecological relationships between Asteraceae-rich field margins, aphid abundance, and hoverfly community structure.

In addition to higher floral diversity, bean aphids were more abundant in Lilongwe, prompting higher movement of aphidophagous hover flies into the bean fields for prey consumption (Colley & Luna, 2000). Thus, both bottom-up (floral resources) and top-down (prey availability) factors appear to jointly structure hoverfly communities in these systems. This observation aligns with the findings of Santos et al. (2018), who reported that hoverfly diversity in various habitats is influenced by factors such as floristic composition, aphid species and abundance. The implication is that incorporating Asteraceae plants into field margins could effectively attract a greater number of predatory hoverflies. These observations suggest that both floral resources availability and prey density jointly influence hoverfly community structure in smallholder systems, suggesting a potential role in aphid predation within these systems, although direct predation rates were not quantified in this study.

While observed patterns are consistent with enhanced biological control in maize-bean intercropping systems, but the observational design limits inference on underlying causal mechanisms. The associations reported may be influenced by unmeasured or uncontrolled factors. In addition, broader landscape contexts and other management practices may also have influenced the observe ecological patterns. Consequently, the finding should be interpreted as associations with biological control processes.

Conclusions

The study provides evidence that hoverflies are closely associated with aphid populations and are likely to play a vital role in the biological control of bean aphids in smallholder production systems. Maize-bean intercropping combined with diverse field margin vegetation was associated with reduced aphid incidence and abundance. These factors support hoverfly populations which are highest in crop fields surrounded floral field margins. These findings provide actionable evidence for smallholder farmers to recognise the importance of field margin vegetation where encouraging flowering plants can be used as a low-input strategy for strengthening crop production and reducing reliance on synthetic pesticides. While this study focused on hoverflies as key aphid predators, other natural enemies were not documented and may also have contributed to aphid suppression. Future research should expand the scope to include multiple predator taxa to provide a more comprehensive understanding of biological control dynamics. Future research should also include multi-season and multi-site monitoring to assess the long-term ecological stability of hoverfly-based aphid control.

CRediT authorship contribution statement

Yamikani Kaliwo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ellen Kumchenga:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Yolice L.B Tembo:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Trust K. Donga:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Vernon H. Kabambe:** Writing – review & editing, Supervision. **John Chipeta:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Data curation. **Philip C. Stevenson:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Steven R. Belmain:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.2026.106102.

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