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RESEARCH

First record of *dacus vertebratus*, *dacus frontalis* and initial observations on *zeugodacus cucurbitae* in the ruzizi plain, albertine rift zone, DRC

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Abstract

Fruit flies (Tephritidae) are among the most destructive pests of cucurbit crops, causing significant yield and quality losses. In the Ruzizi Plain (eastern Democratic Republic of Congo), the species composition and infestation dynamics of these species remained undocumented. This study assessed the diversity and infestation levels of fruit flies on cucumber, watermelon, and squash across three sites: Luvungi, Sange, and Kiliba. Six species were recorded, with *Dacus frontalis* and *Dacus vertebratus* emerging as the most dominant. *D. vertebratus* showed a strong preference for cucumber (infestation rate: 3.660), followed by *D. frontalis* (2.679), while squash showed the lowest levels of infestation. *Bactrocera dorsalis* exhibited minimal infestation (0.508), reflecting its primary association with tree fruits. The Shannon–Wiener index (H′ = 1.733) indicated moderate to high species diversity. Multivariate analysis revealed crop-specific assemblages and interspecific interactions, especially between *D. frontalis* and *B. dorsalis*. The first formal detection of *D. vertebratus* and *D. frontalis* in this region suggests possible ecological range expansion. These findings highlight the need for targeted pest control strategies, particularly for cucumber, integrating species-specific behaviours, host preference, and local agroecological factors. Future research should explore climate impacts, parasitoid activity, pheromone traps, and push-pull methods to improve integrated pest management.

Keywords Albertine rift · *Dacus* · Invasive species · Pest Management · Tephritidae · *Zeugodacus*

Introduction

The family Tephritidae (Diptera) comprises over 5,000 described species, with approximately 12% belonging to the genera *Bactrocera* Macquart and *Zeugodacus* Hendel (Sood et al. 2024). Nearly one-third of these species develop within fresh fruits (Steck et al. 2022). Among them, around 200 species are recognized as economically significant pests such as they have been shown by Chandrashekhar et al. (2024) and Sapkota et al. (2024). Approximately 250

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species are reported by Aluja et al. (2024); they are currently listed as potential quarantine pests in international trade.

Despite stringent quarantine protocols, polyphagous fruit fly species have rapidly spread across tropical and subtropical regions, causing substantial economic losses (Ganie et al. 2022; Hoskins et al. 2023). The impacts of these pests include the rejection of damaged fruits, depreciation of infested orchards, and significant financial losses that undermine market efficiency (Oyesuntimi 2023). Papadopoulos et al. (2024) reported that the fruit flies present a major obstacle to fruit and vegetable exports by increasing production and treatment costs due to phytosanitary regulations. Fulano et al. (2021) have shown the quarantine status of fruit flies has intensified surveillance and control expenditures, particularly in regions where alternative management strategies are limited.

Mujuka (2023) emphasized that fruit fly infestations detrimentally affect horticultural production at multiple levels. At the farm level, infested orchards lose commercial value, as damaged fruits are often unfit for fresh consumption or processing, with losses reaching up to 100% in severe infestations. This compromises orchard viability and may result in investment losses or bankruptcy. Van Zyl (2019) reported the trade restrictions on infested zones limit access to export markets, reducing foreign exchange earnings. Domestically, produce from affected areas sells at reduced prices, diminishing farmers' incomes. Consequently, national revenues decline due to lower taxes and duties on fruit sales. Charlton et al. (2021) have shown these economic challenges may culminate in unemployment, layoffs, and increased rural-to-urban migration. According to Otieno (2023) and Mello Garcia et al. (2024), the threat posed by Tephritidae is especially severe in Africa, where the horticultural sector supports up to 40 million jobs directly or indirectly.

In the Democratic Republic of Congo (DR Congo), fruit fly research has highlighted their ecological and economic importance. Virgilio et al. (2011) conducted comparative studies on species diversity in tropical forests and agroecosystems. Rubabura et al. (2019) characterized fruit fly diversity and abundance in the Albertine Rift, and Rubabura and Muhigwa (2022) assessed infestation rates in *Solanum aethiopicum* (African eggplant), *Solanum lycopersicum* (tomato), and *Capsicum* spp. (pepper) in eastern DR Congo.

Mugisho (2024) reported the Ruzizi Plain, an important agroecological zone shared by DR Congo, Rwanda, and Burundi, has experienced rapid growth in fruit and vegetable cultivation over the past decade. Batulani et al. (2023) have shown, its warm, humid climate provides optimal conditions for fruit fly development. Munyakazi (2023) reported the expansion of cucurbit cultivation especially watermelon, cucumber, and squash has increased production and trade to nearby markets such as Bukavu, Uvira, Bujumbura, and Bugarama. However, cucurbit production in the region is frequently affected by insect pests, particularly tephritid fruit flies, which have been reported to cause substantial yield and quality losses in tropical production systems across Africa (De meyer and Ekesi 2016 ; Mutamiswa et al. 2021). Quantitative estimates of economic losses remain poorly documented for eastern Democratic Republic of the Congo. Despite the growing importance of cucurbit production in the Ruzizi Plain, quantitative information on fruit fly-associated yield losses and their economic consequences remains scarce. This knowledge gap limits the development of evidence-based pest management strategies for smallholder farming systems in eastern DRC.

Despite this, there remains a paucity of data on the presence, distribution, species composition, and infestation rates of tephritid fruit flies in the Ruzizi Plain. This knowledge gap limits the design and implementation of effective pest management strategies. Therefore, it is critical to document the fruit fly species inhabiting this region, their host associations among cucurbit crops, and their relative abundance and epidemiological characteristics. This study aimed to assess the diversity, abundance, and epidemiological parameters of fruit flies infesting the three most widely cultivated cucurbit crops in the Ruzizi Plain of South Kivu, Democratic Republic of the Congo: watermelon (*Citrullus lanatus*), cucumber (*Cucumis sativus*), and squash (*Cucurbita pepo*).

Materials and methods

Study area

The study was conducted in the Ruzizi Plain, an extensive region spanning three Great Lakes countries: Burundi, Rwanda, and the Democratic Republic of Congo. The Plain covers a total area of approximately 1,750 km² (175,000 hectares), distributed unevenly among the Imbo Plain in Burundi (93,000 hectares), the Ruzizi Plain in DR Congo (80,000 hectares), and the Bugarama Plain in Rwanda (2,200 hectares) (Furaha 2018). Recent surveys have identified watermelon, cucumber, and squash as the most widely cultivated cucurbit crops in the Ruzizi Plain, particularly within Burundi and the DR Congo (Rushigira et al. 2021). The villages of Luvungi (2°51′54.29″ S, 29°0′17.96″ E), Sange (3°2′10.82″ S, 29°11′20.76″ E), and Kiliba (3°7′36.01″ S, 29°8′52.01″ E) are recognized as the primary collection and marketing centres for these fruits, serving both local and regional trade.

The Ruzizi Plain lies at an average altitude of approximately 800 m and experiences a tropical climate characterized by temperatures ranging from 17 °C to 30 °C. Annual rainfall varies between 600 and 1,100 mm, distributed over roughly 120 to 140 rainy days per year. The dominant vegetation consists primarily of grassy savanna, interspersed with shrub and thorny steppe, while gallery forests occur along the 117 km course of the Ruzizi River. Soils in the region are predominantly sandy-clay to clay-sandy in texture and are of alluvial origin, deposited by rivers descending from the surrounding mountainous areas.

Survey design and data collection

A preliminary survey was conducted in the Ruzizi Plain, specifically at Luvungi, Kiliba, and Sange, in December 2023 to identify cucurbit fruit markets and determine the origins and probable cultivation areas of the fruits. The survey in these cultivation zones enabled the collection of attacked fruit samples from Luvungi, Sange, and Kiliba, with respective quantities of 26.6 kg, 30 kg, and 25.6 kg for cucumber, watermelon, and squash (Trombik et al. 2023). The collected fruits were transported to the laboratory, where they were maintained on a sterilized layer of sand exceeding 1 cm in depth. Samples were placed on sand bed lining plastic trays sized appropriately for the volume of each sample. Fruits from the three cucurbit species were distributed into nine wooden cages measuring $60 \times 30 \times 30$ cm. Each fruit sample was weighed, and the cage was labelled with the harvest and incubation dates, fruit weight, origin, and geographical coordinates.

The fruits were incubated in the Entomology Laboratory of Lwiro (2°14′21.0″ S, 28°48′40.2″ E; 1,695 m a.s.l.) under controlled conditions (23 ± 2 °C and 60–80% relative humidity) to allow larval development and adult emergence, after which morphological identification was performed (Fontdevila Pareta et al. 2023). Fruits were placed in rearing cages constructed from wooden frames and covered with fine nylon insect-proof mesh. Larvae emerging from infested fruits were allowed to pupate in a moist substrate placed at the bottom of the cages. Pupae were maintained until adult emergence, and emerged adults were supplied with water and granulated sugar. Adults were kept alive for approximately one week to ensure complete cuticle sclerotization and coloration before identification. Developmental durations of immature stages were not recorded systematically during the present study. Previous studies have shown that larval development of cucurbit-infesting tephritid fruit flies generally lasts 5–10 days, followed by a pupal stage of approximately 7–14 days, depending on species and environmental conditions (De meyer and Ekesi 2016). Therefore, the present study focused on species identification and adult emergence rather than on developmental biology parameters, ensuring full morphological development before preservation for analysis. Weekly, sand was gently sieved to collect pupae, which were transferred to small ventilated plastic boxes until adult emergence. Some emerged flies were preserved in 95% ethanol. A monitoring sheet was maintained to track sample development. On average, larvae were observable after two weeks, and adult fruit flies emerged within three to four weeks post-incubation (Di Ilio and Cristofaro 2021). The total number of emerged adults was recorded by fruit type, with insects subsequently identified to species level and stored. Each specimen was labelled with relevant information, including cucurbit crop, fruit weight, collection date, and location. Samples were individually numbered and tracked for complete traceability, following recommendations by Arvaniti et al. (2024), and Zhao et al. (2024).

Insect specimens were shipped in Centrifugal Tube 12 (TPP) and preserved for identification. Dead adults were morphologically identified using a monocular microscope and identification keys, including White and Elson-Harris (1992), Virgilio et al. (2014), Ben Othmen et al. (2025) and and online identification resources (Georgen 2024).

Flies were sexed, and species counts were recorded to determine sex ratios within populations. The emergence rate was calculated as the number of adult flies relative to collected pupae; larval counts were not estimated due to the inability to destroy fruits without interrupting development (Jing et al. 2019). Infestation rates (adults/kg) were analysed across cucurbit hosts using a site-based replication ($n = 3$ sites). Mean values ± standard errors were calculated across sites. The infestation rate was estimated as the number of emerged flies per fruit weight (Adedeji et al. 2020). Data analysis focused on fruit fly abundance, species diversity, and distribution across the Ruzizi Plain.

Statistical analysis

In the present study, Pearson's correlation was evaluated through a pairwise scatterplot matrix incorporating a categorical grouping variable to investigate co-occurrence patterns among six fruit fly species (*Bactrocera dorsalis*, *Dacus bivittatus*, *Dacus frontalis*, *Dacus punctatifrons*, *Dacus vertebratus*, and *Zeugodacus cucurbitae*). In ecological entomology and pest management contexts, such visual matrices offer a powerful tool to detect species associations and ecological niche overlaps across diverse agro-ecological settings.

The diagonal elements of the matrix display the univariate distribution of each species, typically represented by histograms or density curves, providing an initial assessment of relative abundance and variance. The off-diagonal scatterplots illustrate bivariate relationships, revealing the degree of correlation or segregation between species pairs. The inclusion of a categorical grouping variable such as host plant species or sampling site represented by color-coded data points, enhances interpretive clarity by allowing detection of context-dependent species interactions that may vary according to crop type or geographic location.

Specifically, each point in the matrix corresponds to an observation from a trapping site or crop sample, with point colours indicating the host plant (watermelon, cucumber, or squash) or sampling site. This exploratory approach is critical for understanding ecological dynamics and pest pressures. Similar analyses have been employed to evaluate fruit fly incidence on different host plants and remain essential for optimizing integrated pest management (IPM) strategies (Sciarretta et al. 2018).

Before conducting the one-way analysis of variance (ANOVA), tests for homogeneity of variances and normality were performed to verify the underlying statistical assumptions (Das et al. 2023). Subsequently, ANOVA was carried out to assess the effect of species on emergence rates. This preliminary analysis aimed to detect any overall differences in emergence rates among the six Tephritidae species infesting the studied cucurbit crops.

A Principal Component Analysis (PCA) was conducted (Bunnell et al. 2020) to explore the structure of fruit fly assemblages (Tephritidae) associated with three cultivated cucurbits watermelon, cucumber, and squash across three distinct agroecological sites: Luvungi, Sange, and Kiliba, located in the Ruzizi Plain (DRC). The PCA determined whether fruit fly community composition is influenced by host plant species and geographic location.

To analyze the diversity of the fruit fly species in our dataset, we calculated the Pearson (D) Diversity Index, which is based on the Shannon-Wiener index (Rahmawati et al. 2025). This index takes into account both the number of species and their relative abundances, providing a measure of the diversity within the community by using R 4.2 software (R Core Team 2023). The diversity of fruit flies in the Ruzizi Plain is the key indicator of ecological status and agricultural pressures in this region, which spans across the Democratic Republic of Congo (DRC), Rwanda, and Burundi.

Results

Morphological identification of fruit fly species

Morphological analysis of collected specimens from cucurbit agroecosystems in the Ruzizi Plain led to the identification of six distinct fruit fly species belonging to the Tephritidae family. The genus *Dacus* was the most abundant, with 566 individuals characterized by fully fused abdominal tergites forming a single smooth plate without laterally overlapping sclerites. Four species were distinguished within this genus (*D. vertebratus*, *D. frontalis*, *D. punctatifrons*, and *D. bivittatus*) based on diagnostic features such as thoracic patterning, femoral colouration, wing markings, and tergite structure (Fig 1).

Fig. 1 Taxonomic composition of fruit fly species (Tephritidae) identified morphologically from specimens collected across three sampling sites (Kiliba, Sange, and Luvungi) in the Ruzizi Plain. A total of six species were classified into three genera: *Dacus* (566 specimens), *Zeugodacus* (130 specimens), and *Bactrocera* (61 specimens). Species identification was based on external morphological traits, including the structure of abdominal tergites, thoracic markings, femoral colouration, and wing patterns (e.g., costal bands). Within Dacus, four species were recorded (**a**) *D. vertebratus*, (**b**) *D. frontalis*, (**c**) *D. punctatifrons*, and (**d**) *D. bivittatus*, along with one species of (**e**) *Zeugodacus* (*Z. cucurbitae*) and one of (**f**) *Bactrocera* (*B. dorsalis*). All six species were detected at each site, indicating broad ecological distribution and host associate

The genus *Zeugodacus*, represented by 130 specimens, exhibited separated tergites and distinct wing markings, with only one species identified (*Z. cucurbitae*). The 61 specimens of *Bactrocera* were recognized by separated tergites and overlapping lateral sclerites, with *B. dorsalis* being the sole representative.

The simultaneous presence of all six species at the three sampling locations Kiliba, Sange, and Luvungi demonstrates their broad ecological adaptability and strong association with cucurbit hosts in this region. These findings underscore the importance of these species as major pests and provide a critical baseline for developing site-specific integrated pest management (IPM) strategies.

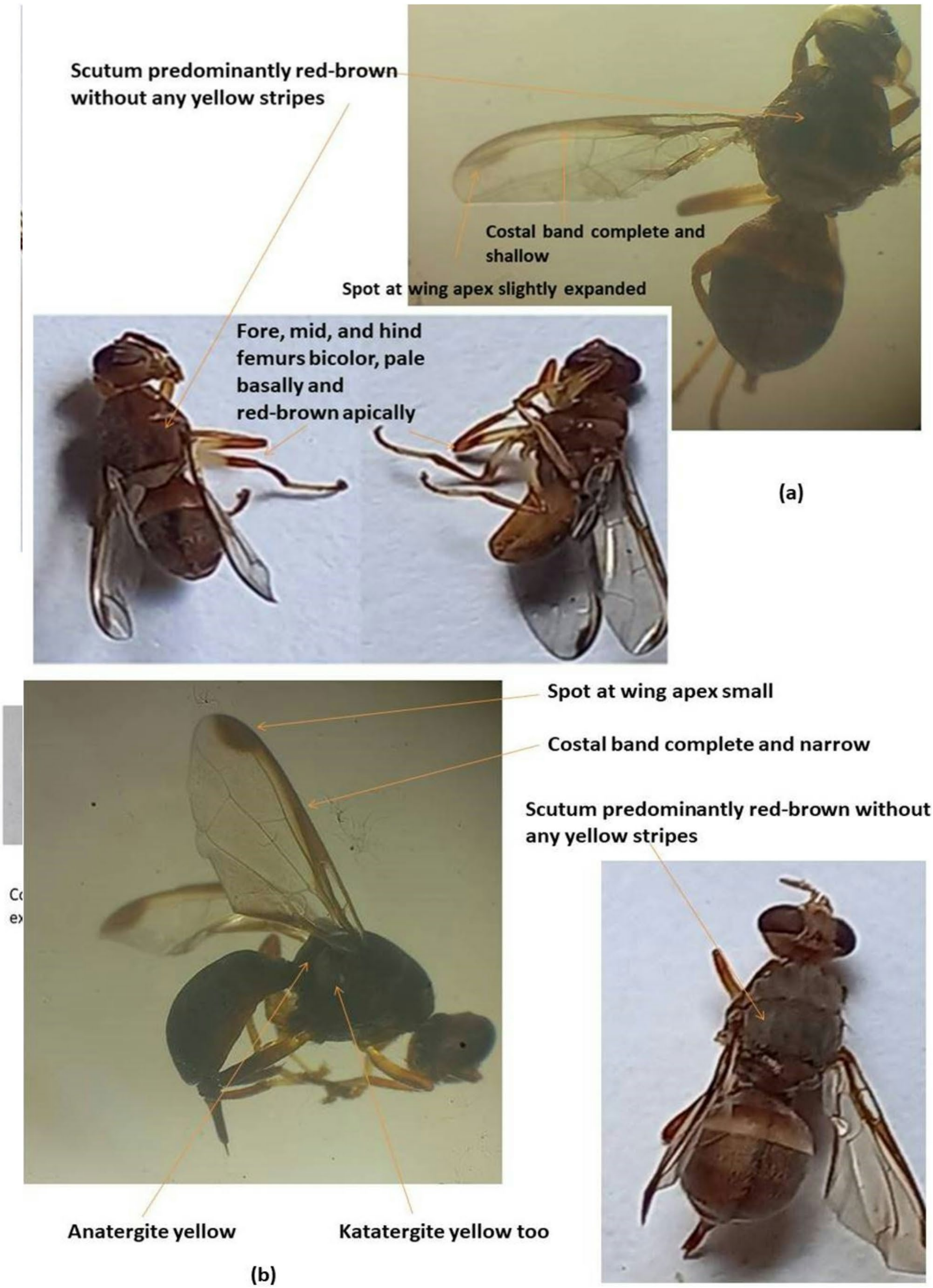
Host plant preferences

Occurrence of tephritid species in cucurbits fruits

The PCA revealed clear spatial and crop-related differentiation in fruit fly assemblages, indicating distinct ecological patterns driven by host plant specificity and local environmental factors. These findings suggest niche partitioning among Tephritidae species in tropical cucurbit systems and underscore the importance of site- and crop-specific integrated pest management (IPM). For example, the dominance of *Dacus frontalis* in cucumber plots at Luvungi and the high abundance of *D. punctatifrons* in squash at Sange highlight the need for targeted surveillance and control strategies tailored to specific crop site combinations (Figs. 2, 3 and 4).

Sex ratio of tephritidae species populations

The sex ratios of Tephritidae species emerging from watermelon, cucumber, and squash were strongly male-biased across all host plants (Table 1). *Dacus bivittatus* exhibited



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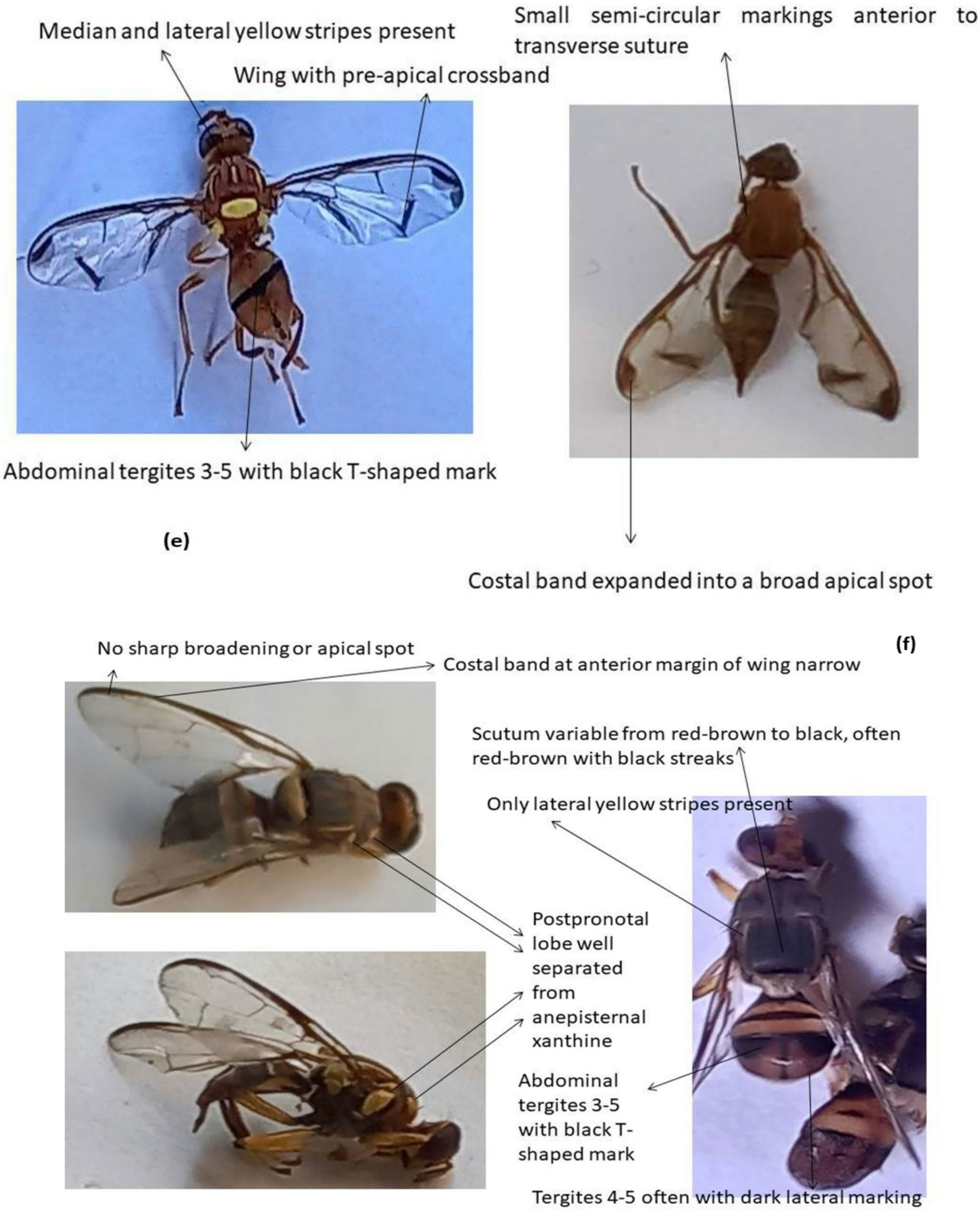

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sex ratios ranging from 5.5:1 to 7.2:1 males per female, while D. frontalis showed ratios between 5.7:1 and 8.43:1.

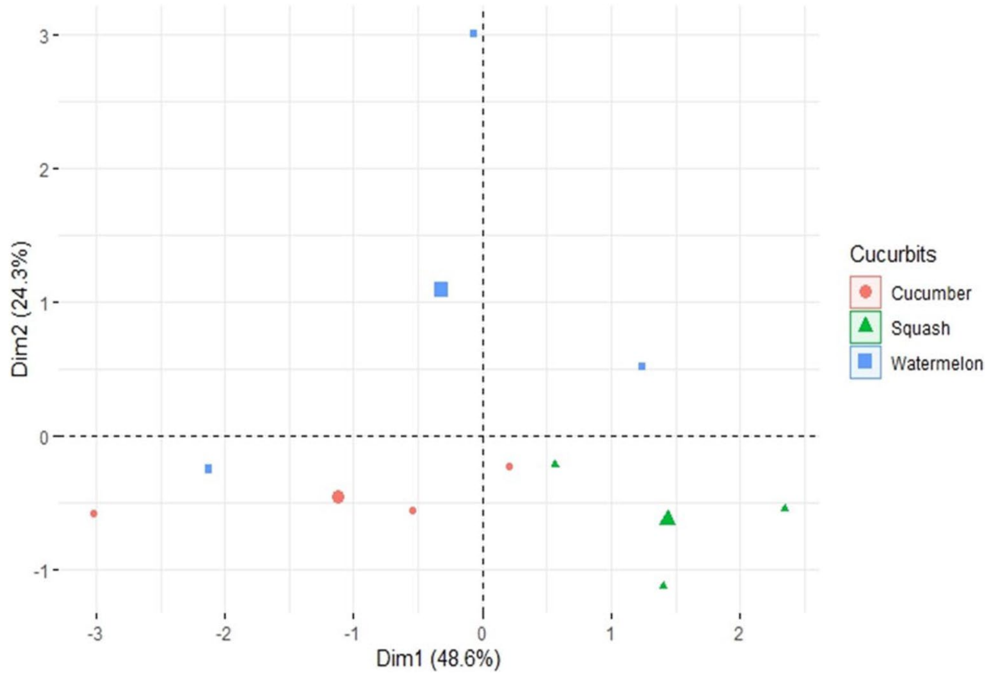

Fig. 2 Principal Component Analysis (PCA) of fruit fly species composition according to cucurbit host type showing the first two principal components accounted for 75.6% of the total variance in fruit fly community composition. PC1 (48.6%) primarily discriminated samples based on the dominance of *Dacus frontalis* and *D. vertebratus*, effectively separating sites and host plants with high abundances of these species from those where they were less prevalent. PC2 (24.3%) captured a secondary ecological gradient driven by the relative prevalence of *Zeugodacus cucurbitae* and *D. punctatifrons*, reflecting ecological preferences that appear less dependent on total fly abundance but more on specific crop or site conditions

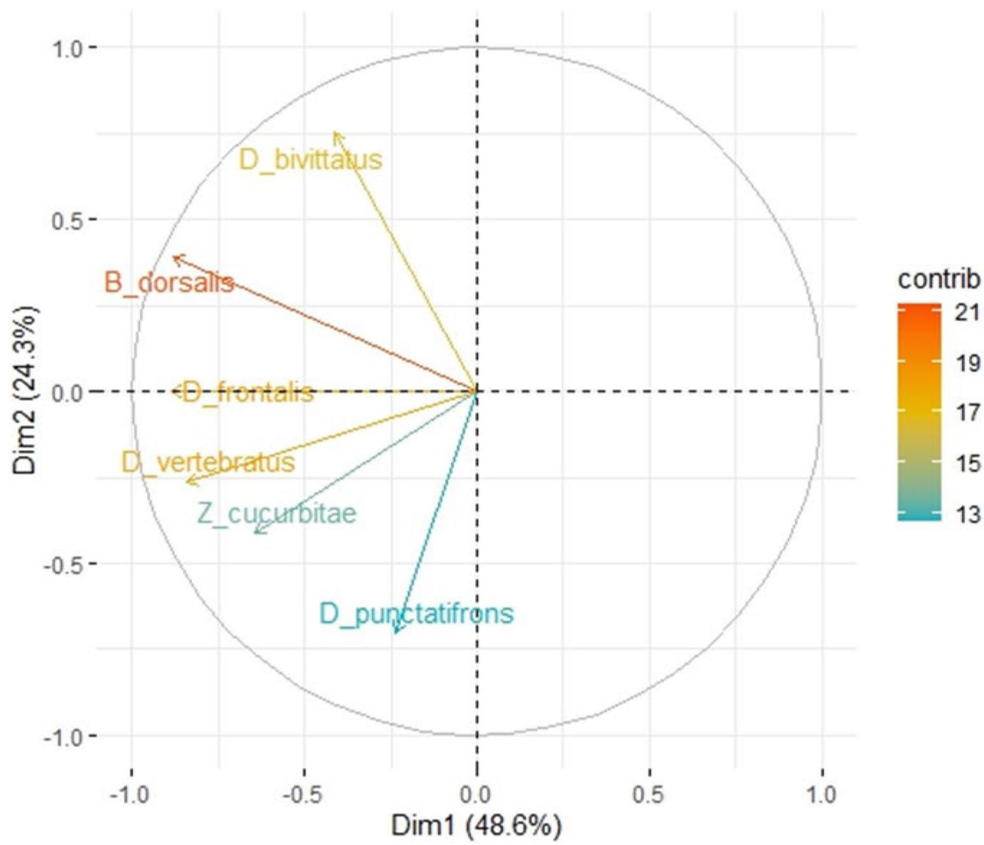

Fig. 3 Variables of Principal Component Analysis (PCA) of fruit fly species showing the analysis of the species vectors in the PCA biplot revealed notable patterns of correlation. *Dacus frontalis* and *D. vertebratus* exhibited a strong positive correlation, suggesting overlapping ecological niches or similar host preferences. In contrast, *Bactrocera dorsalis* and *D. punctatifrons* were positioned in opposite directions, indicating potential competitive exclusion or distinct host-use strategies among these species

Similarly, *Zeugodacus cucurbitae* displayed male-biased sex ratios ranging from 4.88:1 to 7.8:1 across the three cucurbit hosts.

Chi-square tests revealed no significant differences in sex ratios among watermelon, cucumber, and squash for *D. bivittatus* (χ^2 = 0.30, df=2, P=0.86), *D. frontalis* (χ^2 = 0.82, df=2, P=0.66), and *Z. cucurbitae* (χ^2 = 1.15, df=2, P=0.56). These results indicate that although sex ratios were consistently male-biased, the magnitude of this bias did not differ significantly among host crops.

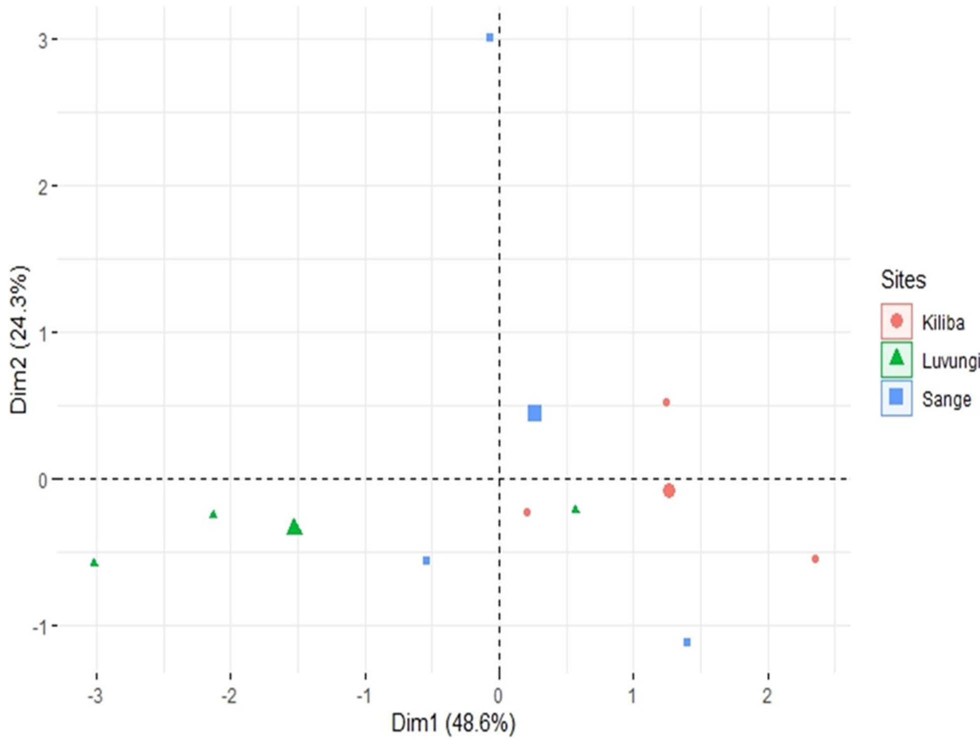

Fig. 4 Principal Component Analysis (PCA) of fruit fly species composition according to sampling site revealed distinct ecological groupings among fruit fly assemblages. Samples from Luvungi, particularly those from cucumber plots, were strongly associated with *Dacus frontalis*, suggesting a host site preference. At Sange, squash samples clustered closely with *D. punctatifrons*, indicating a possible species-specific attraction to squash in this locality. In contrast, samples from Kiliba showed a more even distribution, with moderate associations with *Zeugodacus cucurbitae* and *D. vertebratus*. The clustering of samples in the PCA biplot, supported by confidence ellipses, highlights the combined influence of the host plant and sampling site as key structuring factors in Tephritidae community composition

Table 1 Sex ratio (male) of *Tephritidae* species populations by cucurbit host emerging from watermelon, cucumber, and squash in the Ruzizi Plain, and results of Chi-square tests comparing sex ratios among host crops. The sex ratio is expressed as the number of males per female for each species on the different host plants

		Sex ratio			χ^2	df	*P*-value
Genus	Tephritidea						
	Species	Watermelon	Cucumber	Squash		2	0.860
Dacus	*D. bivittatus*	(36:5)7.20	(33:6)5.50	(28:4)7.00	0.30	2	0.664
	D. frontalis	(59:7)8.43	(61:10)6.10	(37:6)6.17	0.82	–	–
	D. punctatifrons	(19:0) ∞	(41:0) ∞	(37:0) ∞	–	–	–
	D. vertebratus	(50:0) ∞	(97:0) ∞	(30:0) ∞	–	–	–
Bactrocera	*B. dorsalis*	(25:0) ∞	(23:0) ∞	(13:0) ∞	–	–	–
Zeugodacus	*Z. cucurbitae*	(39:8)4.88	(39:5)7.80	(34:6)5.67	1.15	2	0.562

For *Dacus punctatifrons*, *D. vertebratus*, and *Bactrocera dorsalis*, all emerged individuals were males, resulting in infinite male-to-female ratios and precluding statistical comparison among host plants. The persistent predominance of males may be associated with species-specific biological traits, differential survival during immature stages, or sex-related ecological factors that warrant further investigation.

Emergence rates

Emergence rates varied among fruit fly species and cucurbit hosts. *Dacus frontalis* exhibited emergence rates of 0.271 ± 0.011, 0.212 ± 0.045, and 0.221 ± 0.007 on watermelon, cucumber, and squash, respectively. Similarly, *D. vertebratus* showed emergence rates of 0.199 ± 0.020 on watermelon, 0.310 ± 0.008 on cucumber, and 0.155 ± 0.007 on squash. Intermediate emergence rates were observed for *D. bivittatus*, ranging from 0.128 ± 0.014 on cucumber to 0.174 ± 0.048 on watermelon. *D. punctatifrons* exhibited emergence rates of 0.075 ± 0.005, 0.133 ± 0.012, and 0.191 ± 0.025 on watermelon, cucumber, and squash, respectively (Fig 5).

Bactrocera dorsalis recorded the lowest emergence rates across hosts, with values of 0.103 ± 0.009 on watermelon, 0.074 ± 0.006 on cucumber, and 0.066 ± 0.008 on squash. *Zeugodacus cucurbitae* exhibited emergence rates of 0.179 ± 0.038 on watermelon, 0.142 ± 0.009 on cucumber, and 0.203 ± 0.013 on squash.

These differential emergence patterns highlight cucumber as particularly susceptible to infestation by several Tephritidae species, especially *D. vertebratus* and *D. frontalis*, whereas squash appears less vulnerable. Such host-specific trends provide valuable insights for targeted pest

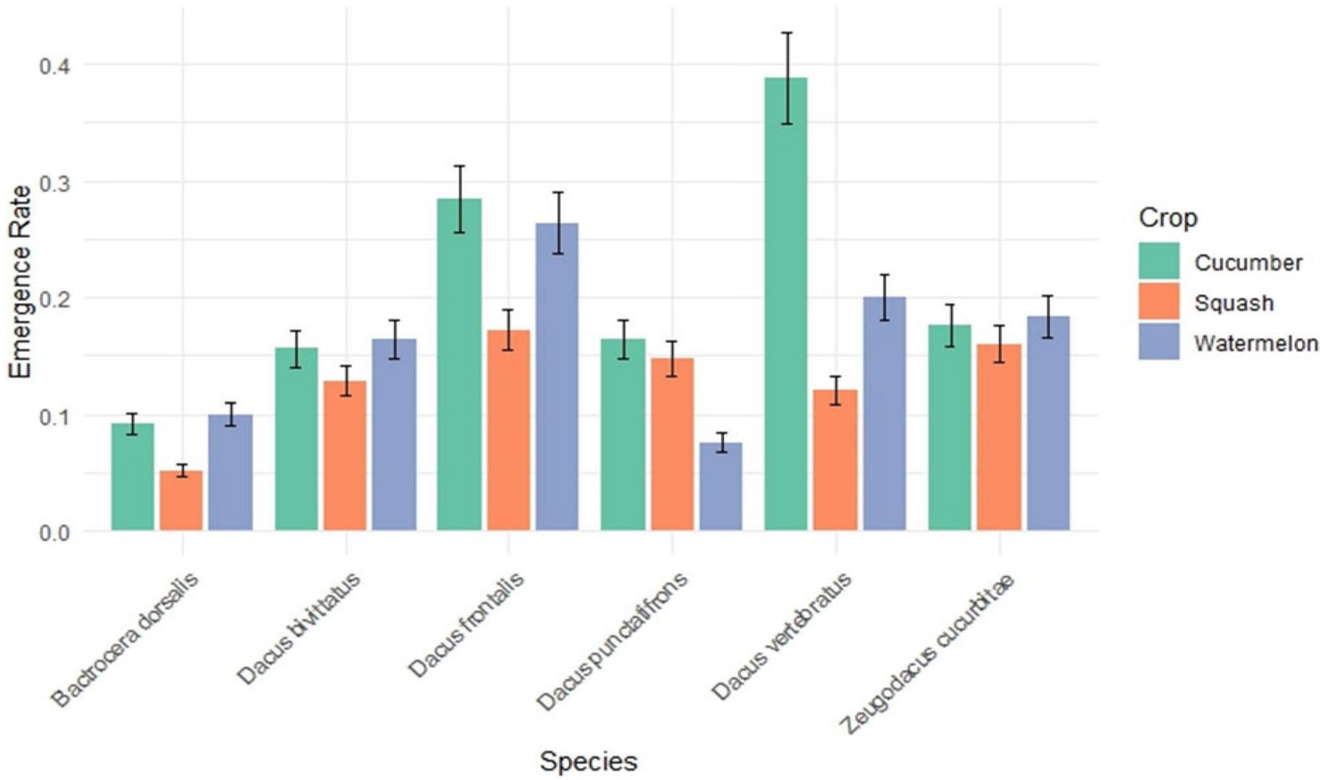

Fig. 5 Emergence rates of six Tephritidae species were assessed across three major cucurbit hosts watermelon, cucumber, and squash in the Ruzizi Plain. Emergence rate, defined as the proportion of adult flies emerging from infested fruits, serves as an indicator of infestation intensity and species performance on each host

management strategies, underscoring the need to prioritize control measures on cucumbers to reduce crop losses.

It is important to emphasize that statistical analyses incorporating measures of variability, such as standard errors or confidence intervals, are required to confirm the significance of these differences. Furthermore, environmental variables, seasonal fluctuations, and methodological factors should be considered when interpreting these results.

Overall, the findings underscore the dominance of *D. frontalis* and *D. vertebratus* as key pests of cucurbit crops in the Ruzizi Plain. Effective integrated pest management programs should integrate species-specific host preferences and infestation dynamics to promote sustainable cucurbit production in this agroecological zone (Fig 6).

Although the *p-value* approached the conventional significance threshold ($p<0.05$), it did not reach statistical significance, suggesting only a marginal effect of species on emergence rate. These findings imply that, under the conditions of this study, the emergence rates are relatively similar across species.

Fruit fly infestation rates

Dacus vertebratus (3.660 ± 0.025) exhibited the highest infestation rate, particularly on cucumber, followed by *Dacus frontalis* (2.679 ± 0.036). Overall, infestation levels were highest on cucumber, intermediate on watermelon, and lowest on squash, indicating that cucumber is the most susceptible host among the studied cucurbits. In contrast, *Bactrocera dorsalis* showed consistently low infestation rates across all cucurbit species (0.508 ± 0.013 to 0.868 ± 0.013), confirming its weak association with cucurbit hosts, likely due to its stronger preference for tree fruits such as mango, guava, and citrus. *Zeugodacus cucurbitae* and *Dacus punctatifrons* displayed intermediate infestation levels, suggesting a moderate level of adaptation to cucurbit hosts compared to the more specialized or dominant species (Table 2).

Diversity of the fruit fly community

The Shannon–Wiener index (H') quantifies species diversity by integrating both species richness (the number of species) and species evenness (the relative abundance of each species). As shown in Table 3, the calculated value of $H' = 1.733$ indicates moderate to high diversity within the fruit fly community. Generally, higher H' values approaching or exceeding 2 reflect greater species diversity. The observed diversity is supported by the presence of multiple species,

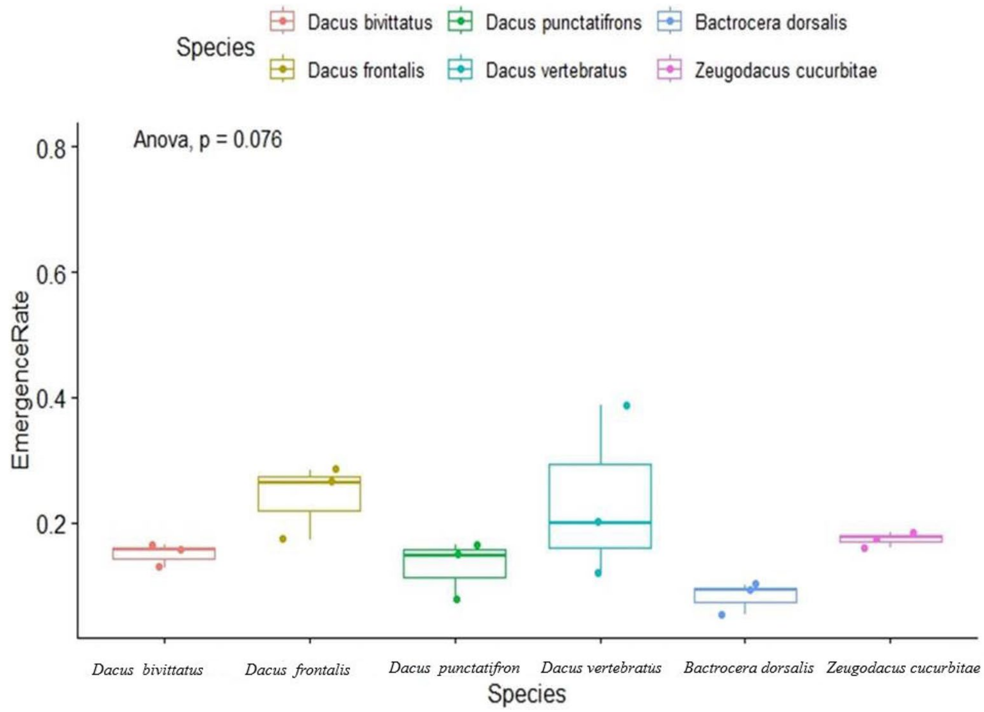

Fig. 6 ANOVA indicated no statistically significant differences in emergence rates among the six fruit fly species ($F_{5,12} = 2.671$, $p = 0.076$)

Table 2 Infestation rates (individuals per fruit) of six fruit fly species *Bactrocera dorsalis* (Bd), *Dacus bivittatus* (Db), *Dacus frontalis* (Df), *Dacus punctatifrons* (Dp), *Dacus vertebratus* (Dv), and *Zeugodacus cucurbitae* (Zc) across three cultivated cucurbit hosts: cucumber, squash, and watermelon in the Ruzizi Plain, DRC highlight patterns of host specificity and relative pest pressure, offering valuable insights into species-level preferences and infestation dynamics within cucurbit agroecosystems. Such information is critical for the development of targeted and crop-specific pest management strategies

Cucurbits	Infestation rate					
	Bd	Db	Df	Dp	Dv	Zc
Cucumber	0.868 ± 0.013	1.472 ± 0.006	2.679 ± 0.036	1.547 ± 0.014	3.660 ± 0.025	1.660 ± 0.013
Squash	0.508 ± 0.013	1.250 ± 0.014	1.679 ± 0.019	1.445 ± 0.009	1.172 ± 0.013	1.562 ± 0.012
Watermelon	0.833 ± 0.008	1.367 ± 0.015	2.200 ± 0.030	0.633 ± 0.008	1.667 ± 0.020	1.533 ± 0.009

Table 3 Diversity metrics of the fruit fly (Tephritidae) community in the Ruzizi Plain summary encompasses species richness, relative abundance, and diversity indices, including the Shannon–Wiener index (H′), number of individuals (*ni*), proportion of individuals (*pi*), sum of squared proportions(Σpi^2), and evenness measures (Pielou's evenness index)

Fruit fly						
Genus	Species	ni	pi	Σ pi^2	H'	Evenness
Dacus	*D. bivittatus*	112	0.1717305	0.1855042	1.732834	0.9671133
Dacus	*D. frontalis*	180	0.2377807			
Dacus	*D. punctatifrons*	97	0.1281374			
Dacus	*D. vertebratus*	177	0.2338177			
Bactrocera	*B. dorsalis*	61	0.08058124			
Zeugodacus	*Z. cucurbitae*	130	0.1479524			

including *Dacus bivittatus*, *Dacus frontalis*, *Bactrocera dorsalis*, and *Zeugodacus cucurbitae*. The relative abundance of *Dacus frontalis* (180 individuals, *pi* = 0.2378) and *Dacus vertebratus* (177 individuals, *pi* = 0.2338) indicates these species are dominant yet do not overwhelmingly monopolize the community structure. Notably, the first recorded occurrences of *Dacus frontalis* and *Dacus vertebratus* in the Ruzizi Plain represent a significant entomological finding, potentially reflecting ecological niche expansion or the impacts of climate change.

Correlation of fruit fly species

The univariate distributions along the diagonal illustrate the abundance patterns of the different fruit fly species. For instance, the narrow and pronounced distribution of

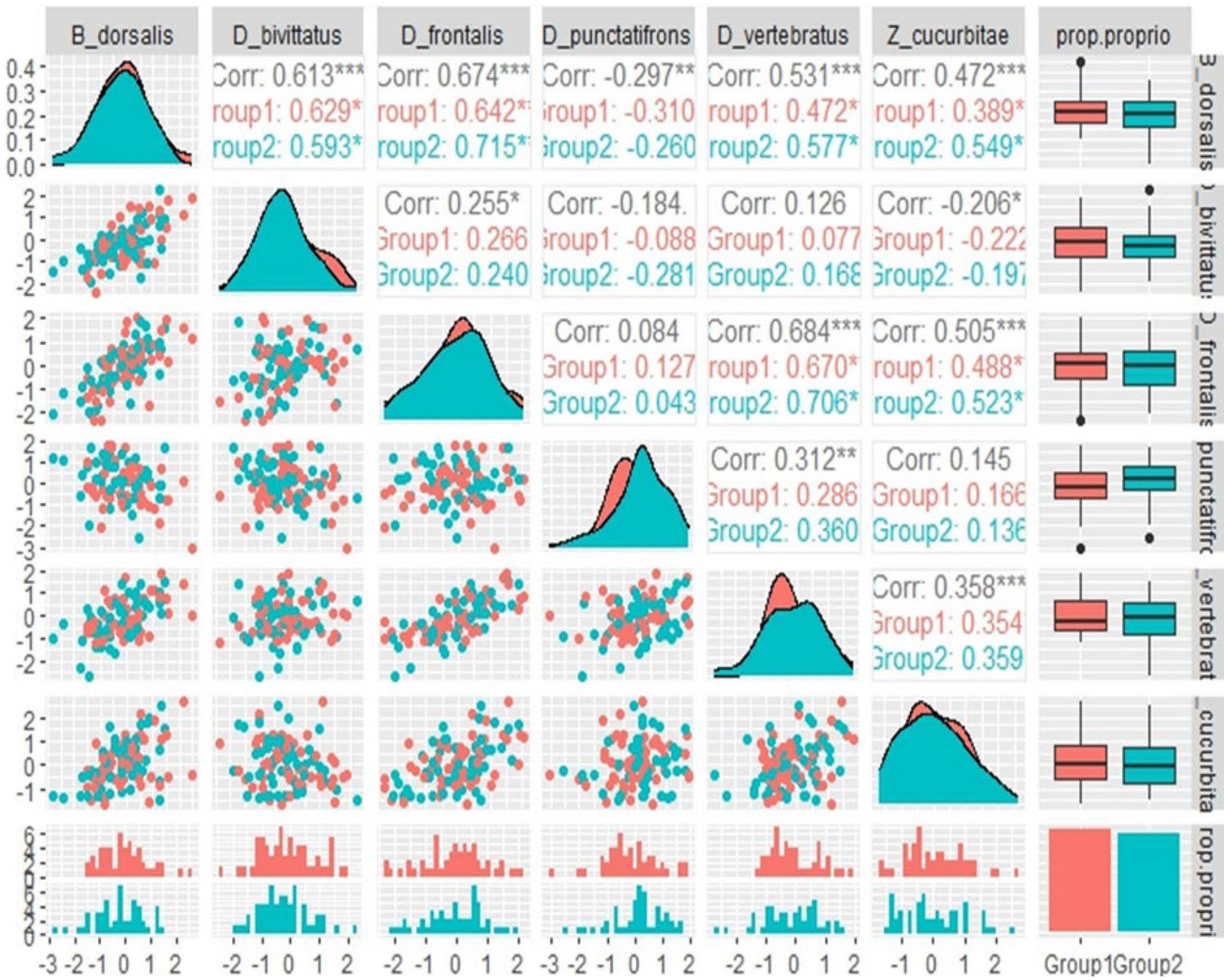

Fig. 7 Pairwise scatterplot matrix showing the univariate and bivariate abundance patterns of six fruit fly species (*Bactrocera dorsalis*, *Dacus bivittatus*, *D. frontalis*, *D. punctatifrons*, *D. vertebratus*, and *Zeugodacus cucurbitae*) collected from cucurbit crops (watermelon, cucumber, and squash) across multiple sampling sites. Diagonal panels display the univariate distributions of species abundances, while the off-diagonal panels represent pairwise scatterplots coloured by the host plant (e.g., red for watermelon). The structure of these distributions and interspecific relationships reveals patterns of dominance, variability, co-occurrence, and potential crop-specific assemblages

Bactrocera dorsalis reflects its consistent dominance across various agricultural contexts, whereas the broader distribution of *Dacus bivittatus* indicates a more variable presence. Off-diagonal scatterplots reveal positive linear relationships, such as the correlation between *B. dorsalis* and *Dacus frontalis*, suggesting frequent co-occurrence and potentially shared ecological preferences or host plant affinities. In contrast, the random scatter of points observed between *Dacus punctatifrons* and *Zeugodacus cucurbitae* suggests a weak association, indicative of distinct ecological niches. The predominance of red points (e.g., representing watermelon) within certain species pairs may reflect crop-specific assemblages. Collectively, these patterns offer valuable insights for targeted pest management by highlighting potential interspecific interactions including shared attractants, synergistic effects, or competitive exclusion, as well as species dynamics unique to each agroecosystem (Fig 7).

Discussion

Morphological analysis of fruit fly specimens collected from cucurbit agroecosystems in the Ruzizi Plain led to the identification of six tephritid species belonging to three genera: *Dacus*, *Zeugodacus*, and *Bactrocera*. The genus *Dacus* was the most abundant, comprising 566 individuals, and was characterized by fully fused abdominal tergites forming a smooth plate without overlapping lateral sclerites a distinguishing trait of this genus (David et al. 2019). Four species within *Dacus* were identified (*D. vertebratus*, *D. frontalis*, *D. punctatifrons*, and *D. bivittatus*) based on morphological features including thoracic patterning, femoral colouration, wing markings, and tergite structure, consistent with the diagnostic keys provided by Mafirakurewa (2016). In contrast, 130 specimens belonging to the genus *Zeugodacus* were characterized by separated tergites and distinct wing markings, with only *Z. cucurbitae* identified. The 61 specimens of *Bactrocera*, distinguished by separated tergites and overlapping lateral sclerites, were all attributed to *B. dorsalis*, a well-known invasive pest of tropical fruits (Drew and Hancock 2022).

The concurrent presence of all six species across the three surveyed sites Kiliba, Sange, and Luvungi demonstrates a high degree of ecological adaptability and confirms their strong association with cucurbit crops in this agroecological zone. These results align with earlier findings from other parts of sub-Saharan Africa, which reported *Dacus* spp. as a dominant pest of cucurbits (Layodé et al. 2020; Waithaka et al. 2023). This co-occurrence further implies overlapping ecological niches and potential interspecific competition among species utilizing the same host plants (Facon et al. 2021). Importantly, this study presents the first confirmed record of *D. vertebratus* and *D. frontalis* in the Democratic Republic of Congo, particularly within the Ruzizi Plain. While the presence of *D. punctatifrons*, *D. bivittatus*, *Z. cucurbitae*, and *B. dorsalis* had previously been documented in the country (Virgilio et al. 2011; Rubabura et al. 2019), the detection of *D. vertebratus* and *D. frontalis* expands the known geographical distribution of these species in Central Africa. This extension is consistent with more recent distributional records reported by Vasudha et al. (2019) and Zeng et al. (2019), suggesting potential shifts in species range, possibly influenced by climate change and agroecological transitions. The presence of a diverse complex of tephritid pests presents a significant threat to cucurbit production and highlights the need for site-specific integrated pest management (IPM) strategies tailored to the local pest assemblage. Monitoring programs and taxonomic updates remain crucial to inform timely management interventions and to prevent further spread or outbreaks of economically damaging species (Aluja et al. 2024). These findings serve as a critical baseline for future ecological, behavioural, and control studies aimed at improving cucurbit production systems in the region.

The results of the principal component analysis (PCA) revealed pronounced spatial and crop-specific differentiation in fruit fly assemblages across the Ruzizi Plain. This differentiation suggests distinct ecological patterns primarily influenced by host plant specificity and localized environmental factors. Such structuring indicates potential niche partitioning among co-occurring Tephritidae species, supporting the hypothesis that host plant identity plays a key role in shaping fruit fly community composition within tropical cucurbit agroecosystems (Mullens et al. 2024; Hendrycks et al. 2025). The observed variation in species dominance across sites and crops further emphasizes the ecological plasticity and habitat preferences among fruit fly species. Notably, *Dacus frontalis* exhibited marked dominance in cucumber (*Cucumis sativus*) plots at Luvungi, while *D. punctatifrons* was particularly abundant in squash (*Cucurbita pepo*) fields at Sange. These patterns highlight the need for site- and crop-specific integrated pest management (IPM) strategies, as general control measures may be insufficient or misaligned with local pest pressures (Wyckhuys et al. 2024). Tailoring surveillance and control efforts to these specific crop-location combinations will enhance the efficacy of pest suppression strategies and reduce unnecessary chemical inputs. Furthermore, such knowledge contributes to a better understanding of fruit fly population dynamics and interspecific interactions, which are critical for developing sustainable management plans in diversified smallholder farming systems common in sub-Saharan Africa (Assèdé et al. 2025).

A pronounced male bias was observed across all Tephritidae species and host crops. Similar male-dominated populations have been reported in other fruit fly studies and may result from sex-specific differences in survival, emergence patterns, behaviour, or attraction to semiochemicals and host-related cues. The complete absence of females in *Dacus punctatifrons*, *D. vertebratus*, and *Bactrocera dorsalis* is particularly noteworthy. Although the underlying mechanisms remain unclear, this pattern may reflect sex-specific behavioural traits, differential mortality during immature stages, or temporal segregation between males and females. Similar observations have been reported in Tephritid populations where males and females differ in their responses to environmental and chemical stimuli (Luo et al. 2024). Because no significant differences in sex ratios were detected among watermelon, cucumber, and squash for *D. bivittatus*, *D. frontalis*, and *Z. cucurbitae*, host plant species does not appear to influence the degree of male bias in the emerging populations under the conditions of the present study. This pronounced male dominance cannot be attributed to the use of male-specific attractants such as methyl eugenol or cue lure, since these compounds were not used during the survey. Male-biased sex ratios reported in Tephritidae studies are often associated with the use of such attractants, which selectively capture males in several species (Singh and Müller 2025). However, in the present study, the observed bias may instead reflect inherent behavioral or ecological differences between males and females, including variation in activity patterns, mobility, or differential susceptibility to the trapping method used. Alternatively, ecological or physiological factors such as male-biased emergence patterns, lekking behaviour, or sampling time windows may have influenced the observed sex ratios (Bath et al. 2023). From a pest management perspective, these findings have important implications. Male-biased captures challenge the accuracy of population estimates when extrapolated from trap data and complicate strategies such as the Sterile Insect Technique (SIT), which depends on balanced or predictable sex ratios in natural populations (Blondel 2021).

The emergence patterns observed in this study highlight *Dacus frontalis* and *Dacus vertebratus* as the dominant fruit fly species infesting cucurbit crops in the Ruzizi Plain, with overall emergence rates of 0.704 and 0.664, respectively. This predominance is consistent with previous observations in East and Central Africa, where members of the *Dacus* genus have been reported as key cucurbit pests (Kambura 2016). The pronounced preference of *D. vertebratus* for cucumber (emergence rate: 0.388) suggests a high degree of host specificity, a trend noted for some *Dacus* species which exhibit oviposition and larval development preferences linked to host plant volatiles and nutritional composition (Vasudha and Agarwal 2019). Conversely, *D. frontalis* displayed more balanced emergence rates across cucumber (0.212 ± 0.045), squash (0.221 ± 0.007) and watermelon (0.271 ± 0.011), suggesting it is less host-restricted and capable of exploiting a broader range of cucurbits. Such generalist behaviour is ecologically advantageous in diverse cropping systems, enabling population persistence even when preferred hosts are scarce (Deconninck et al. 2025). The presence of multiple competent hosts nearby may further facilitate overlapping generations and increased infestation pressure. The low emergence rate of *Bactrocera dorsalis* (0.244) contrasts with its status as a major pest of fruit crops in sub-Saharan Africa, particularly mango and guava (Mutamiswa et al. 2021). Its reduced performance on cucurbits in this study may reflect either ecological exclusion by dominant *Dacus* spp. or an inherent lack of adaptation to cucurbit hosts, as also reported in Tanzanian and Kenyan studies (Rwomushana and Tanga 2016). *Dacus bivittatus* emerged consistently but moderately across all cucurbits, reinforcing its categorization as a generalist with wide host adaptability but generally lower infestation intensity (Kambura 2016). Meanwhile, the emergence values of *Zeugodacus cucurbitae* although globally known as a major cucurbit pest (Ahn et al. 2022) were surprisingly low in this study. This discrepancy may be due to climatic influences, competition, or microhabitat conditions limiting its development and survival (Colinet et al. 2025). It may also indicate methodological variation in trapping or emergence collection, highlighting the need for further focused evaluation. The differential emergence patterns suggest that cucumber is the most susceptible host, particularly to *D. vertebratus* and *D. frontalis*, while squash appears to be less vulnerable. This aligns with previous reports indicating that cucumber's high moisture content and thin pericarp make it particularly attractive and suitable for oviposition and larval development (Ansari et al. 2019). The lower emergence of squash could be attributed to its tougher rind and potentially less favourable nutritional profile (Borecka and Karaś 2025). These findings have significant implications for integrated pest management (IPM). Species-specific host preferences must be considered when developing control strategies. For instance, mass trapping, attractant lures, and biological control methods such as parasitoid release should prioritize high-risk crops like cucumber (Hoskins et al. 2023; Miano 2024). Additionally, the timing of interventions should be synchronized with the peak activity periods of *Dacus spp*., which are influenced by seasonality, rainfall, and crop phenology (Pak 2020). Environmental variables such as temperature, humidity, and elevation as well as methodological factors like trap placement and bait type should also be taken into account to enhance the robustness of interpretations (Einoder et al. 2018).

The study revealed that *Dacus vertebratus* (3.660 ± 0.025) and *Dacus frontalis* (2.679 ± 0.036) exhibited the highest infestation rates among the tephritid species collected, with cucumber being the most affected host plant, followed by watermelon. Squash, on the other hand, experienced the lowest infestation. This pattern suggests that cucumber provides more favourable conditions (e.g., softer skin, higher water content, and attractive volatiles) for the oviposition and larval development of these *Dacus* species. These results are consistent with earlier reports indicating cucumbers are among the most susceptible cucurbits to *Dacus* infestations in tropical regions (Ben Othmen et al. 2025). The relatively high infestation levels of *D. vertebratus* and *D. frontalis* on cucumber may also reflect the overlap between host plant phenology and peak fly activity, which is influenced by temperature, rainfall, and host availability (Boulahia-Kheder 2021). The preference for cucumbers by these species reinforces the need for crop-specific integrated pest management (IPM) approaches, including baiting and exclusion techniques during peak fruiting periods. In contrast, *Bactrocera dorsalis* demonstrated a significantly lower infestation rate (0.508) across all cucurbit species surveyed. This finding aligns with the established ecological niche of *Bactrocera dorsalis* Hendel 1912, which primarily targets fleshy tree fruits such as mango (*Mangifera indica* L.), guava (*Psidium guajava* L.), and citrus (*Citrus* spp.) (Al Ansari 2023). Its minimal presence in cucurbit fields may be due to its weaker attraction to cucurbit volatiles and its lower oviposition success on cucurbit tissues. These differential infestation patterns emphasize the importance of understanding species-host relationships for effective pest forecasting and control. Management strategies should prioritize highly susceptible crops like cucumber, using targeted lures such as cue-lure for *Dacus* spp. and methyl eugenol traps for *B. dorsalis*, where relevant (Kean et al. 2024).

The present findings demonstrate that *Dacus vertebratus* (3.660 ± 0.025) and *Dacus frontalis* (2.679 ± 0.036) are the most aggressive fruit fly species infesting cucurbit crops in the Ruzizi Plain, with cucumber emerging as the most susceptible host. Watermelon was the second most infested crop, while squash consistently recorded the lowest infestation levels. These results suggest a strong host preference for *D. vertebratus* and *D. frontalis* for cucumber, potentially due to the crop's physical and chemical characteristics, such as softer epidermal tissue, higher moisture content, and attractive volatile organic compounds (Kambura et al. 2018). These traits may facilitate oviposition and larval development, rendering cucumber a favourable host for these *Dacus* species. The infestation patterns observed are in line with earlier research showing the preference of Dacus spp. for specific cucurbit crops. For instance, *Dacus bivittatus* and related species have been reported to infest cucumbers more heavily than other cucurbits due to similar host attractiveness factors (Waithaka et al. 2023). Furthermore, the observed host-specific behaviour underscores the ecological adaptation of these species to cucurbits, particularly during peak fruiting seasons when host availability and environmental conditions favour their population growth (Mauck and Chesnais 2020). In contrast, *Bactrocera dorsalis* recorded the lowest infestation rate (0.508 ± 0.013) across the cucurbit hosts. Fadul (2021) reported the relatively low incidence of this species is likely attributable to its well-documented host preference for fleshy tree fruits, such as mango (*Mangifera indica*), guava (*Psidium guajava*), and citrus (*Citrus* spp.). *B. dorsalis* shows limited adaptation to cucurbits; both in terms of oviposition behaviour and larval survival, and its minor presence in the cucurbit fields of the Ruzizi Plain may reflect accidental landings rather than a targeted infestation. The differential infestation rates among species highlight the importance of developing crop-specific integrated pest management (IPM) strategies. Targeting dominant pests like *D. vertebratus* and *D. frontalis* particularly in cucumber production through baited traps, exclusion netting, and cultural controls, could significantly reduce crop losses and reliance on synthetic insecticides (Miano 2024).

The Shannon diversity index ($H' = 1.733$) suggests a moderate level of diversity within the cucurbit-infesting fruit fly assemblage in the Ruzizi Plain. The assemblage included several species, namely *Dacus frontalis*, *Dacus vertebratus*, *Dacus bivittatus*, *Zeugodacus cucurbitae*, and *Bactrocera dorsalis*. The highest relative abundances were recorded for *D. frontalis* (180 individuals; $p_i = 0.2378$) and *D. vertebratus* (177 individuals; $p_i = 0.2338$), although no single species exceeded a relative abundance of 0.25. This relative balance contributes to the moderately high diversity index and suggests a stable fruit fly community structure in the region. Importantly, the first recorded occurrences of *Dacus frontalis* and *Dacus vertebratus* in the Ruzizi Plain represent a novel entomological finding. These species have been largely documented in West and Central Africa (De Meyer and ekesi 2016; De Meyer et al. 2023), and their presence in the eastern DRC may signal ecological niche expansion, likely facilitated by anthropogenic factors such as land-use change and crop intensification. Additionally, climate variability and warming trends can influence the distribution of Tephritid species by altering suitable habitat zones and host availability (Qin et al. 2021).

The graphical representation of univariate distributions along the diagonal axes offers insights into the relative abundance and ecological behaviour of key fruit fly species. The sharply peaked and narrow distribution of *Bactrocera dorsalis* suggests its stable occurrence in the Ruzizi Plain, possibly linked to its strong host fidelity, reproductive capacity, and widespread distribution across Africa and Asia (Zimowska et al. 2024). This consistent dominance aligns with findings from various agroecological contexts where B. *dorsalis* is known to exhibit high adaptability and competitiveness (Su et al. 2025).

In contrast, the broader distribution pattern of *Dacus bivittatus* may reflect its generalist tendencies and variable infestation rates depending on host availability, microclimatic conditions, or interspecific competition (Motswagole 2017). The observed interspecific relationships in the off-diagonal scatterplots, such as the positive correlation between *B. dorsalis* and *Dacus frontalis*, indicate potential ecological overlaps possibly due to shared host plants or mutual responses to similar environmental cues. Co-occurrence of species often points to similar oviposition behaviour, resource partitioning, or simultaneous attraction to common lures, such as methyl eugenol or cue-lure, which are used in fruit fly surveillance and control programs (Tarno et al. 2022).

On the other hand, weak or random associations, such as that between *Dacus punctatifrons* and *Zeugodacus cucurbitae*, suggest that these species may exploit different ecological niches or possess distinct seasonal and spatial dynamics (Tarimo et al. 2025). The weak correlation could also reflect host plant specificity or differing susceptibility to abiotic factors like temperature, rainfall, or crop phenology. The ecological separation may reduce direct competition, allowing multiple species to coexist in a shared agroecosystem (Ndlela et al. 2020).

Furthermore, the color-coded points such as the predominance of red markers representing watermelon highlight the role of specific cucurbit crops in structuring species assemblages. Crop-specific dominance, for instance of *Dacus vertebratus* on cucumber or *B. dorsalis* on watermelon, can provide valuable cues for crop rotation planning and spatially explicit pest management strategies (Zhou et al. 2024).

Study limitations

An additional limitation of this study concerns species identification. Fruit fly specimens were identified using morphological characters and published taxonomic keys. Although this approach is widely used in routine tephritid surveys and pest monitoring, no molecular confirmation was conducted. Consequently, potential misidentification among morphologically similar species cannot be entirely excluded. However, the species recorded in this study are well documented in East and Central Africa, and diagnostic morphological traits were consistent with established identification keys and reference descriptions. Future studies incorporating DNA-based methods, such as COI barcoding, would improve species-level resolution and help confirm cryptic or closely related taxa.

Conclusion

The results demonstrate that *Dacus frontalis* and *Dacus vertebratus* are the dominant Tephritidae species infesting cucurbit crops in the Ruzizi Plain, with a marked preference for cucumber. These findings highlight the critical need for site-specific and species-specific integrated pest management (IPM) strategies that consider host plant phenology, natural enemy activity, and local agricultural practices. To further enhance the effectiveness of control measures, future research should investigate the roles of climatic variables, parasitoid interactions, pheromone-based monitoring and control, and the implementation of push-pull strategies. Such targeted approaches are essential for the development of sustainable and resilient cucurbit production systems in this agroecological zone.

Dacus vertebratus (3.660 ± 0.025) exhibited the highest infestation rate, particularly on cucumber, followed by *Dacus frontalis* (2.679 ± 0.036). Overall, infestation levels were highest on cucumber, intermediate on watermelon, and lowest on squash, indicating that cucumber is the most susceptible host among the studied cucurbits. In contrast, *Bactrocera dorsalis* showed consistently low infestation rates across all cucurbit species (0.508 ± 0.013 to 0.868 ± 0.013), confirming its weak association with cucurbit hosts, likely due to its stronger preference for tree fruits such as mango, guava, and citrus. *Zeugodacus cucurbitae* and *Dacus punctatifrons* displayed intermediate infestation levels, suggesting a moderate level of adaptation to cucurbit hosts compared to the more specialized or dominant species.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval This study involved the collection, rearing, and identification of insect specimens associated with cultivated cucurbit crops. No human participants, human biological materials, personal data, vertebrate animals, or animal experimentation were involved. Therefore, approval from an Institutional Review Board (IRB) or Ethics Committee was not required. Consent to participate was not applicable because the study did not involve human participants, interviews, questionnaires, or personal data collection. Likewise, the Human Ethics Declaration is not applicable. Because this research did not involve human participants or vertebrate animals, ethical standards such as the Declaration of Helsinki were not applicable. The study was conducted in accordance with institutional and national regulations governing scientific research and biodiversity sampling in the Democratic Republic of the Congo. All applicable international and national guideline were followed. All procedures performed in studies were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

Competing interests The authors declare no competing interests.

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