Afrotropical Diptera entomofauna conservation: technology application for Diptera identification in Afro-subtropical savannah ecosystems, Zimbabwe.

By

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Submitted in fulfillment of the requirements for the MPhil in Entomology

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July 2025

CHINHOYI UNIVERSITY OF TECHNOLOGY

RELEASE FORM

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TITLE OF PROJECT: Afrotropical Diptera entomofauna conservation: technology application for Diptera identification in Afro-subtropical savannah ecosystems, Zimbabwe.

DEGREE FOR WHICH

THESIS WAS PRESENTED: MPhil in Entomology

YEAR THIS DEGREE GRANTED: 2025

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Main Supervisor's Consent

Date: 3/07/2025

Dedication

This research is dedicated to my mother, Mary Matengo, for all her patience, support, and effort, though she never understood what I was studying. A special thanks goes to my supervisors, Prof. Tarakini, Prof. Musundire, and Dr. G. Tarakini, for their unwavering supervision and support throughout the research process.

Abstract

Flies in the insect order Diptera are important to humans as providers of food, medicines, and for ecosystem services such as pollination and disease vectors, among others. Patterns of Diptera diversity, distribution, and conservation status remain less explored in the Afrotropical region (AR). For some areas, Diptera inventories are incomplete, some keys for certain families are outdated, under revision, or incomplete, making the work for taxonomists in this field extremely difficult. Despite advancements in Artificial Intelligence (AI) and machine learning (ML), there has been relatively limited focus on the application of these tools for the identification of Afrotropical Diptera (AD). This work focused on exploring fly diversity and distribution in a typical protected area in Zimbabwe, Matopos National Park (MNP). This study involved sampling dipterans in three habitats (i.e., mountains, woodlands, and grasslands) and across seasons (i.e., cool-dry, hot-dry, and hot-wet seasons) in MNP, between December 2021 – April 2025, except the year 2023. Sampling was done using pan traps of three colours (yellow, white, and blue) mixed with a drop of liquid soap to break surface water tension. A total of 1838 individuals were collected across habitats and seasons. Of these, 58 dipterans were identified to species level, and 94 genera belonging to 29 Diptera families. The GLM (Generalized linear model) results revealed that species abundance was highest in GL (Grasslands), and Mt (Mountains), but least in the WL (Woodlands). Furthermore, 2022 had the highest species abundance, but 2025 had the least abundance. Species richness was highest in GL, while lowest in WL. However, Hw (Hot-wet) had the highest richness, while Hd (Hot-dry) had the least richness. Similarly, 2022 had the highest species richness, while 2025 had the least richness. Regarding Shannon diversity, GL had the highest diversity, while Mt had the least diversity. Hd had the highest diversity, while Cd (Cool-dry) had significantly lower species diversity. The year 2022 had the highest diversity, on the contrary, species diversity was significantly low in 2024. The logistic regression models revealed that the probability of encountering Anthomyiidae, Muscidae, and Platystomatidae were high during the Cd compared to other seasons, whereas the probability of Asilidae, Rhiniidae, and Tabanidae was high in Hw. However, the probability of encountering the family Lauxaniidae were high during the Hd. A model for species identification was trained on Google Teachable Machine 2.0, exported as a TensorFlow Lite, and integrated into a mobile application to identify 30 species. The 90 images (i.e., 3 images from each morpho-species) and the confusion matrix were used to test for the accuracy of the application. The application retained an accuracy score of 100% which makes it promising for enhanced species identification. This study concluded that Diptera sampling is still insignificant in the AR, particularly in Zimbabwe, where world-heritage sites like MNP lack inventories and checklists of AD. The success of the mobile application offers a tremendous opportunity in automated species identification, especially in resource-limited countries like Zimbabwe. More trainings must be done to raise awareness of dipteran pollination in ecosystems.

Keywords: Diptera diversity, Afrotropical species, mobile application, artificial intelligence, machine learning, Matopos national park.

Acknowledgements

I thank the Chinhoyi University of Technology for providing the necessary resources. I am grateful to my university and field supervisors, Prof. T. Tarakini and Prof. R. Musundire, respectively, for guiding me throughout the project. I thank Dr. G. Tarakini for mentoring throughout the research process and allowing me to use her research equipment. I am also grateful to Tanaka H. Masocha, Mike Kambeni, Patience Chitupa, Ethel Chikwaro, Catherine Fundikwayo, Chipo Kadziso, Nozithelo Moyo, Wendy Nyoni, Joyce Mujuru, Arnold Tsvigu, Mazvita Ndiringepi, and Tafara Shava for the emotional support they gave during my research.

Acronyms

MNP	Matopos National Park
GTM	Google Teachable Machine
NHMZ	Natural History Museum of Zimbabwe

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Chapter 1

1.1 Chapter introduction

The chapter outlines the overall aim, a series of specific objectives, research questions, and hypotheses. It also outlines the problem statement that gave birth to this research and the overview of this work (Chapters 1 – 6).

1.2 General introduction

Dipteran fauna (two-winged or true flies) is one of the largest and taxonomically diverse insect groups after Coleoptera and Lepidoptera, with over 160,042 extant species, described within 10,000 genera, 130 extant families, 22 - 32 super-families, 8 - 10 infraorders, and 2 suborder (Nematocera and Brachycera), with an estimated of one million species yet to be discovered (Kirk-Spriggs & Sinclair, 2017; Sarwar, 2020). Of the ~ 160,042 species, ~20,350 species described with 108 families occur in the Afrotropical region (Kirk-Spriggs & Sinclair, 2017), of which four Diptera families (Glossinidae, Marginidae, Mormotomyiidae, and Natalimyzidae) are endemic to the Afrotropical region, even though two families (Glossinidae and Natalimyzidae are known from the fossil records in Europe and North America) (Kirk-Spriggs & Sinclair, 2017). Hence, species with limited distribution should be monitored because their limited distribution causes them to be more vulnerable than widely distributed groups/families/species.

Flies have successfully managed to colonize all continents, except the open seas and the interiors of glaciers (Courtney et al., 2017). Despite dipteran fauna playing critical ecosystem roles as pollinators (with Syrphidae being considered the second largest group of pollinators after honeybees), decomposers, and their integral part in food webs, their ecological contributions are often outshined by their ill repute as disease vectors (e.g. malaria-transmitting *Anopheles* mosquitoes) and agricultural pests (e.g. *Ceratitis* fruit flies), which cost global economies billions annually in healthcare and crop losses (Onah et al., 2015; Grisales et al., 2016; Chinula et al., 2018; Heve et al., 2021; Doumbe-Belisse et al., 2021; Ebhodaghe et al., 2022; Li et al., 2023; Herrera et al., 2024) . It is because of this ill reputation that has led to their contributions to pollination have been overlooked in favor of more charismatic insect groups

(Raguso, 2020). Hence, the phrase "Don't forget the flies" has been used to change the ill reputation of dipteran fauna (Raguso, 2020).

Disparities in Diptera research have been noted, with research efforts remaining heavily biased toward the Global North, leaving the Global South, where diversity peaks are understudied (Hawkes et al., 2024; Herrera et al., 2024). For many pragmatic reasons, this was because the Global South faced economic and scientific disparities (within Global South countries), limiting their ability to conduct extensive research on Diptera (Bars-Closel et al., 2024). This is worsened by the 'trickle-down' effect from the Global North that often results in research that does not align with the specific needs of the Global South, leading to frustration and a lack of opportunities for local researchers (Parimoo & Mertelsmann, 2023). This often leads to research from the Global South being considered localized rather than universal, affecting the recognition and dissemination of their findings. Bridging the gap between these regions through collaboration and equitable resource distribution can lead to a better understanding of diversity in the Global South.

The AR is one of the regions in the Global South (Atkinson, 2021). The region is considered one of the least studied zoogeographical zones for Diptera, despite harboring exceptional diversity. Recent estimates suggest that only 13% of AD species have been formally described, compared to 27% in the Palearctic (Kirk-Spriggs & Sinclair, 2017; Pape, 2009). Furthermore, it is estimated that ~30,000 species are awaiting description in the Afrotropical region (Kirk-Spriggs & Sinclair, 2017). This knowledge gap has profound implications. For example, there are incomplete distribution records of Diptera species in the Global South, while Europe has near-complete Diptera checklists, while countries like Zimbabwe lack even basic inventories for most protected areas. This poses conservation challenges because without baseline data, assessing extinction risks or ecosystem health is impossible. Habitat loss in Africa is accelerating, yet less than 5% of AD are assessed by the IUCN, compared to approximately 30% in Europe (IUCN, 2023).

The understudied nature of Diptera species in the Sub-Saharan Africa (SSA) does not match their economic roles which range from being important pests of both cultivated and wild plants to carriers of deadly diseases like yellow fever, malaria, and dengue viruses, from being decomposers to important pollinators in croplands and protected areas. Fruit flies (Tephritidae and Drosophilidae) are considered the most devastating pests in agricultural production in SSA. These attack crops like citrus, mango, guava, and cucumbers in horticulture production, causing significant losses, hence the need to study Diptera species. Furthermore, medically/veterinary, Diptera species are culprits. For instance, Culicidae, Simuliidae, and Pschodidae are important vectors of tropical diseases. Blood-feeding *Anopheles* sp and *A. meigen* spread diseases like equine encephalitis, west Nile virus, and Rift Valley fever, filariasis, arboviruses, and malaria killing millions of people annually (Kirk-Spriggs & Sinclair, 2017). This is concerning, as Sustainable Development Goals' (SDGs) mandate is to ensure good health and well-being (SDG 3). However, *A. meigen* has been causing epizootics in cattle, sheep, and goats, causing significant losses (Kirk-Spriggs & Sinclair, 2017), thus worsening poverty and lack of protein, particularly in developing countries. Hence, work that tries to identify problem species for disease control is of paramount importance for the wellness of the people.

Different lenses are needed when studying insects. For dipterans, there is a consensus that they are "filthy or dirty," but they play beneficial roles in both cultivated and wild plants. Syrphids/hoverflies are considered the second most important pollinators after bees (Kamdem et al., 2023; Larson et al., 2001; Li et al., 2023), and hoverfly-mediated pollination has been valued at USD300 billion per annum (Li et al., 2023). Unfortunately, dipteran's contribution to pollination has gone unnoticed due in part to attention given to better-known hymenopteran pollinators like the *A. mellifera* (Engel et al., 2021). Fortunately, recognition of non-bee pollinators as alternatives is on the rise, especially in a time when bee populations are on the decline (Dunn et al., 2020; Engel et al., 2021). Despite recent literature proving the effectiveness of Diptera pollination, the knowledge of non-bee-mediated pollination among farmers is poor (Tarakini et al., 2021). Additionally, research towards determining dipteran pollination is poor, especially in a resource-limited country like Zimbabwe.

Zimbabwe, being part of the Southern African biodiversity hotspot, has no comprehensive Diptera checklist for many of its national parks. Matopos National Park (MNP), a UNESCO World Heritage Site, exemplifies this neglect. Its miombo woodlands and granite kopjes likely host unique Diptera communities, yet studies that assess Diptera community assemblages are lacking. This data deficiency has real-world consequences. For instance, climate change impacts that have resulted in shifting rainfall patterns may alter Diptera distributions, but without baseline studies, predictive models are impossible to do. This imbalance stems from historical underfunding, limited taxonomic expertise, and infrastructural gaps in the Global South. While Europe has approximately 1,000 professional dipterists, Africa has fewer than 50, mostly based in South Africa (Kirk-Spriggs, 2023).

The limited availability of trained taxonomists and accessible identification tools in under-resourced countries like Zimbabwe has contributed to the understudied nature of Diptera in Zimbabwe. This is because the traditional identification methods based on morphological keys are often time-consuming and require specialist knowledge, which is not always available to field workers, students, or citizen scientists in the country. Additionally, recent literature has seen advancements in the use of molecular techniques towards Diptera identification, however, the method is still expensive especially in resource-limited countries like Zimbabwe. Recent machine learning advances like the Google Teachable Machine (GTM), a web-based Graphical User Interface (GUI) present novel opportunities to train models based on images, sounds, and poses. Several projects have been trained using GTM and have achieved good success rates (Wong & Fadzly, 2022). For instance, a study in sea-birds achieved 100% (Wong & Fadzly, 2022), another project in seaweed identification achieved 99.42% (Azhar et al., 2024), and a study in the classification of apple diseases and pests achieved 89.5% (Üniversitesi et al., 2024). Several studies have utilized this platform (GTM) on training Diptera species identification and achieved high success rates. For instance, a study in medically and forensically important flies achieved 98% success rate (Ong & Ahmad, 2022), another focused on estimating housefly diversity and achieved 94.10% (Ong et al., 2021). This technique has the potential to revolutionize biodiversity monitoring and taxonomic research. Mobile applications have increasingly become vital tools in biodiversity science, facilitating species identification through user-friendly interfaces, advanced image recognition, and seamless access to digital databases, even in remote and hard-to-reach locations. In the early 2000s, platforms like Project Noah and BirdLog began enabling citizen scientists to document and share wildlife observations via mobile devices (Goëau et al., 2013). By the mid-2010s, apps such as iNaturalist and Pl@ntNet incorporated machine learning to automate species identification from photos, significantly enhancing data collection efficiency (Aristeidou et al., 2021; Goëau et al., 2013; Horn et al., 2018). Today, these tools support a global network of users contributing millions of observations, thereby advancing both scientific research and conservation efforts.

Despite these advances, there remains a notable gap in the development of mobile tools specifically tailored to species in resource limited countries like Zimbabwe to cater for endemic species. Most existing applications are either limited in scope or not region-specific.

This study, intends (i) assess the composition and community structure of Diptera across habitats and seasons in a World-Heritage Site, Matopos National Park, Zimbabwe, and (ii) design and evaluate a mobile application for the identification of Diptera species.

1.3 Problem statement

Dipteran ecosystem services are not well understood and are often underestimated (Raguso, 2020; Ssymank et al., 2008), particularly in a world heritage site like MNP, Zimbabwe. Despite of their economic importance as pollinators, decomposers, fodder, and human food, AD remain understudied. This is primarily due to a lack of dipterists, curators, insufficient, inaccessible taxonomic keys, and funding in the AR, which has worsened the situation (Jordaens et al., 2024), yet the AD is still in what Irwin et al. (2003: 701) and Kirk-Spriggs & Sinclair (2017) termed the "discovery phase". The current taxonomic tools (dichotomous key and molecular techniques) are either time-consuming or expensive/costly to document the AD assemblages in pristine areas like MNP before they go extinct. Tools like mobile applications have been developed to identify insects in general, yet they are not tailored to identify local dipterans. The lack of such tools has contributed to insufficient Diptera sampling in world heritage sites like MNP. To meet the Global Taxonomy Initiative (GTI) framework of documenting biodiversity, fast and efficient taxonomic tools are needed. Further, the diversity and community composition of dipteran assemblages in pristine, undisturbed environments are not well understood. Many studies in the past focused on bee pollination and tsetse diptera, yet 71 families of diptera contain flower-visiting diptera, visiting over 555 flowering plant species (Larson et al., 2001). Furthermore, patterns of diptera diversity across different habitat types or their current conservation status and population trends remain unknown in protected areas such as Matopos NP. It can be expected that high diversity of diptera species could be harbored in such ecosystems due to the unique habitats and micro-climates created by granite kopjes and low-lying valleys characterizing MNP (Hubbard, 2018). Despite the advances in ML and AI, there has been relatively less work devoted to its application to diptera identification. This study aims to address this need and contribute to the conservation of AD in MNP.

1.4 Aim

Assessing the composition and community structure of Diptera across habitats and seasons in MNP, and using an innovative mobile application for their identification.

1.5. Specific objectives

1. To assess the composition and diversity of Diptera species across different habitats (mountains, grasslands, and woodlands) and seasons (cool-dry, hot-dry, and hot-wet) in MNP.
2. To develop and evaluate a mobile application for the reliable field identification of AD species.

1.6 Research questions

1. What are the patterns of variation in Diptera composition and community structure across different habitats (mountains, grasslands, and woodlands) and seasons (cool-dry, hot-dry, and hot-wet) in Matopos National Park, and how do environmental factors influence these patterns?
2. What is the accuracy and effectiveness of a newly developed mobile application in identifying AD species?

1.7 Research hypotheses

1. We predict that Diptera composition and community structure in Matopos National Park will vary significantly across different habitats (e.g., grasslands, woodlands, and mountains) and seasons (cool-dry, hot-dry, and hot-wet seasons), with habitat heterogeneity and seasonal changes in temperature and rainfall being the primary drivers of these variations.
2. The creation of a comprehensive database and predictive algorithm allows for rapid and reliable identification of Diptera species, reducing identification time compared to traditional methods.

1.8 Conceptual framework

Having considered the outlined major themes for this study, the conceptual framework proposed for this study is outlined in Fig. 1.1. The framework demonstrates the interconnected factors influencing the development of a mobile application for the identification of Diptera species. Central to this conceptual framework is the goal of designing and evaluating a mobile application, which is facilitated by technological advancements (codeless Google Teachable Machine) and the identification of the sampled specimens.

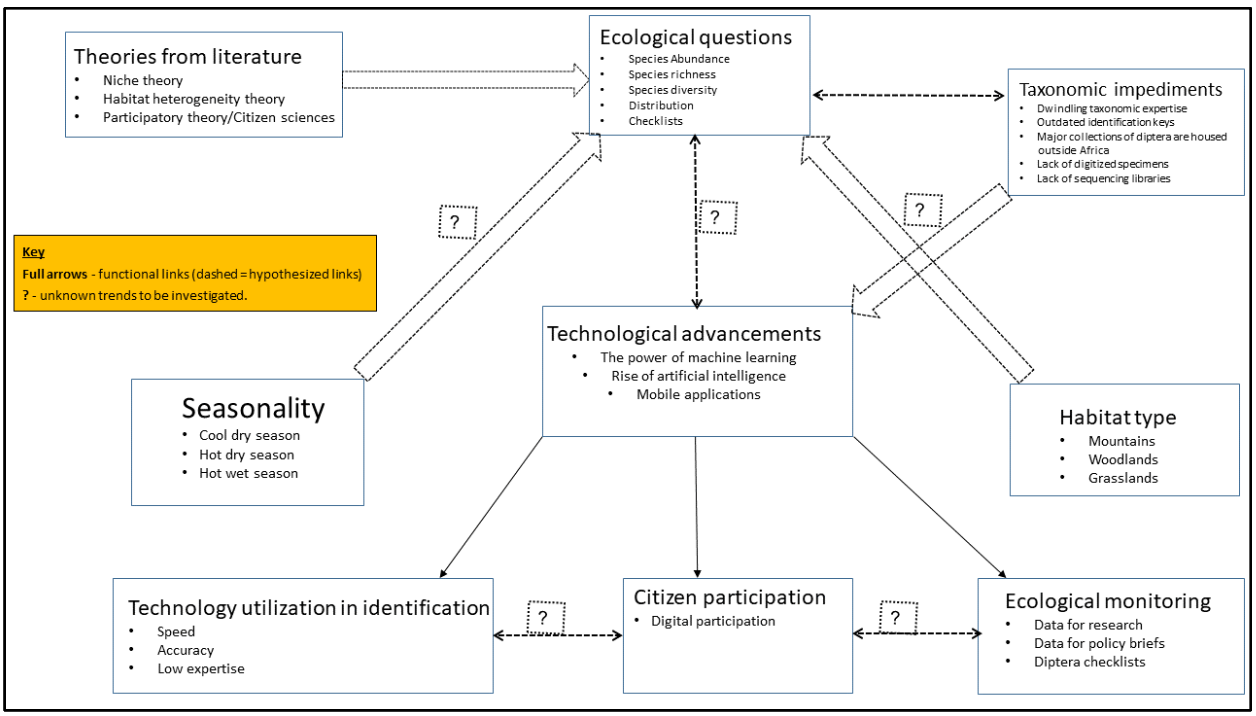

Fig. 1.1: Conceptual framework of this work. The conceptual framework demonstrates the various factors contributing to the understudied nature of AD and the potential effects of seasonality and habitat type on Diptera species.

1.9 Overview of the study

The dissertation is organized into six chapters. The first chapter highlights the background of the research, contextualizes the research problem, outlines the aims, objectives, research questions, and hypothesis of the study.

Chapter 2 provides a comprehensive review of the literature on the biology and distribution of Diptera species, economic importance of Diptera species, history of machine learning, and the efforts that have been put so far towards easing the identification of Diptera species.

Chapter 3 provides a review of the taxonomic developments, distribution, endemism, and economic impact of AD. The findings of this review assisted in identifying gaps in the application of contemporary technologies in the identification of Afrotropical species.

Chapter 4 provides a method for the development of a mobile application for the identification of the AD. With a focus on harnessing the power of machine learning, AI, and image recognition to identify Diptera species.

Chapter 5 provides the composition and diversity of Diptera species across various habitats (woodlands, mountains, and grasslands) and seasons (winter, hot-dry, and hot-wet) in Matopos National Park.

Chapter 6 provides a synthesis of the entire work from Chapters 1-5. It further explains the contribution of this work to education 5.0: Innovation and industrialization.

1.10 Chapter summary

This chapter has justified the need for this study and has shown global and regional trends of Diptera species. Furthermore, the chapter discussed how different studies have harnessed the power of machine learning in automated species identification. It concluded by providing an overview of the research work from chapters 1 – 6.

Chapter 2

Literature review

2.1 Chapter introduction

Identifying insect species is an important step in biodiversity research and insect monitoring. However, traditional ways of morphological taxonomy require specialized expertise, which is lacking in the Afrotropical region. This has contributed to the understudied nature of insects, particularly Diptera species. To counter this, molecular techniques and mobile applications are on the rise to facilitate the identification of Diptera species. This chapter reviews literature on the biology and distribution of Diptera, the intersection of mobile technology, machine learning, and Diptera taxonomy, with a particular focus on developments relevant to the Afrotropical region.

2.2 The biology and distribution of Diptera

Dipteran fauna is a speciose order of single-pair-winged insects commonly known as true-flies/flies/two-winged flies, with the second pair of wings modified into halteres. The name Diptera is derived from the Greek words "di" meaning two, and "ptera" meaning wings. The order Diptera contains ~160,042 species, 10,000 genera, 160 families, 22-32 super-families, 8 - 10 infraorders, and 2 suborders: Nematocera and Brachycera (Kirk-Spriggs & Sinclair, 2017; Mitra, 2010; Winterton et al., 1999). This order is considered one of the largest groups of organisms along with other metropolitan/mega-diversity orders like Coleoptera with >350,000 extant species, Lepidoptera with >120,000, and Hymenoptera with >130,000. Like other insect orders, most dipteran fauna is still considered under-described, with the exact figure ranging as high as 1 million or more (Brown, 2021). Of the ~ 160,000 extant species described, ~20,350 species belonging to 108 families are known from the Afrotropical region (Kirk-Spriggs & Sinclair, 2017: 2). The Afrotropical region is still in the "discovery phase" as noted by Irwin et al. (2003: 701) and (Kirk-Spriggs, & Sinclair, 2017: 2). Four families (Glossinidae, Marginidae, Mormotomyiidae, and Natalimyzidae) are endemic to the Afrotropical region, although the two families (Glossinidae and Natalimyzidae) are known from the fossil records in North America and Europe respectively) (Kirk-Spriggs, & Sinclair, 2017).

Hence, more Diptera inventories are still needed to discover the approximately 30,000 species that are awaiting description as noted by Kirk-Spriggs & Sinclair (2017, 2021). With the currently speed of species discovery of 129 species per annum as estimated by Kirk-Spriggs and Sinclair (2017) in the Manual of Afrotropical Diptera volume 1, hypothetically speaking it would take almost three centuries (231 – 289 years) to reach the end of the *discovery phase* in the Afrotropical region.

Diptera mouthparts range from piercing-and-sucking (e.g., mosquitoes) to "lapping"-type with pseudotracheate labella functioning as a sponge (e.g., house flies) (Busvine, 1980; Kaboré et al., 2023). Their larvae lack true legs, although various kinds of locomotory apparatus range from unsegmented pseudolegs to creeping welts on maggots. The larval head capsule ranges from complete, through partially undeveloped, to complete absence in a maggot head that consists only of the sclerotized mandibles ("mouth hooks") and supporting structures (Cranston & Gullan, 2009).

Dipteran fauna are holometabolic insects, they undergo complete metamorphosis (i.e., egg, larva, pupa, and adult (imago)) (Kirk-Spriggs & Sinclair, 2017). The larvae are adapted to wet conditions and feed on plants and animals. Many adults are detritivores (e.g., *M. domestica* and *D. anilis),* flower feeders (e.g., *A. claripennis*, *A. eclara*, *A. neavei*, and *E. dissimilis*) (Kirk-Spriggs & Sinclair, 2017). Mosquitoes also feed on nectar and plant juices, but females like the *Anopheles* suck blood of mammals. Some feed on leaf litter, leaves, stems, roots, and seed heads, mosses, fungi, and fruits. Conopidae, on the other hand, feed on bees, wasps, and cockroaches, while Sciomyzidae larvae feed on snails or slugs. The environmental and food conditions have mainly determined how flies meet and mate, and explain the diversity of mating behaviors. Visual, acoustic, tactile, and chemical factors are involved in courtship behavior, and even when one factor seems crucial for courtship behavior leading to mating, other factors are generally involved. They may facilitate or even act in synergy (Wicker-Thomas, 2007).

Diptera species have managed to colonize every continent, including Antarctica. They colonized every terrestrial niche in the tropics, subarctic, at sea level, and mountains. The relative percentage of Diptera within the insect fauna rises with latitude (and elevation) as other, less cold-adapted taxa are lost; for instance, over one-half of all insect species recorded from the Canadian high arctic are Diptera species. The number of species described for each region in catalogues is often more indicative of the amount of taxonomic activity directed at a given fauna than the true diversity. For example, the Palearctic Region is the best studied of them all and has more described species than the relatively poorly known, but presumably more diverse, Neotropical Region and the Afrotropical Region. Therefore, more studies are needed in understudied regions.

Diptera species have a bad publicity, they are all regarded as “disease-carrying filth flies”, hence there is little to no public sympathy or interest in their conservation (McEvey et al., 1988). Furthermore, most Diptera are extremely poorly known, and the study of many families is still contingent on the recognition and description of the many undescribed species. An exception to these statements is the Syrphidae, a family that is popular among amateur collectors, especially in Europe.

2.2 Effects of seasonality on Diptera communities

Seasonality has always been noted to influence species activity and distribution. Several studies have demonstrated seasonal variation of species abundance, richness, and diversity, with certain species responding positively to wet seasons than others (Bossche & Hargrove, 2018; Grimaud et al., 2021; Sajjad et al., 2010). A study by Sajjad et al. (2010) discovered a peak species abundance and richness of hoverflies in spring (March-April) than any other reference season. Furthermore, of the most abundant exotic species, *D. malerkotliana, Z. indianus,* and *S. latifasciaeformis* were more importantly represented in the dry season, yet *D. simulans* was more abundant in the rainy period (Coutinho-Silva et al., 2017). Similarly, Zida et al. (2020) noted that a peak of fruit fly population density occurs during the rainy season, while generally low population density was observed in winter (June-July). Additionally, another work by Medina-serrano et al. (2025) noted Diptera families to be particularly abundant and diverse in the wet season. Factors contributing to this are the abundance of food and water for the Diptera species to thrive in the wet season. These findings from other researchers’ warrant sampling of Diptera research across seasons to have a representation of Diptera species across seasons.

2.3 Socio-economic importance

Diptera species play several economic roles, including bio-indicators, biological control, acting as food in food-webs, pollinators (Raguso, 2020), seed dispersers, scavengers, predators, and pests. Many Diptera species are known as pests in croplands. For instance, Agromyzidae are known as leaf, seed, and stem miners attacking both cultivated and wild plants. Fruit flies (Tephritidae and Drosophilidae) are considered one of the most important pests in agriculture and horticulture production in tropical and Southern Africa (sub-tropical and temperate) (Zida et al., 2020). They attack crops such as citrus, mango, guava, and cucumbers, yet their taxonomy remains poor among farmers (Kirk-Spriggs & Sinclair, 2017). Cecidomyiidae attack cereal crops, for instance, *S. midge* and *Stenodiplosis* are well known to reduce cereal crop yields in Africa.

Some groups are of medical/veterinary importance. Families like Culicidae (Mosquitoes), Simuliidae (black-flies), and Psychodidae (drain flies) serve as vectors of tropical diseases. For instance, blood-feeding *Anopheles* sp and *A. meigen* spread diseases like equine encephalitis, West Nile virus, rift valley fever, malaria, filariasis, and arboviruses, claiming millions of lives annually. Additionally, *A. meigen* has posed epizootics in cattle, sheep, and goats in the Afrotropical region and has contributed to economic losses. Hence, studying these tiny but medically important species is important to save the animal husbandry and medical or public health sectors in Sub-Saharan Africa (Kirk-Spriggs & Sinclair, 2017).

While bees (Apidae) dominate the scientific attention in pollination literature, non-bee pollinators have been noted to rival bee populations in pollinator networks, particularly Diptera species. Kearns (2001) noted that at least 71 dipteran families contain anthophilous (those that feed on or frequently visit flowers) species. Furthermore, Buchmann & Nabhan (1998) added that an estimated 14,126 species of Diptera are involved in pollination processes in the tropical world. Syrphidae is arguably considered the second-largest group of pollinators after honeybees, yet dipteran pollination remains understudied. This is largely because the cultural and economic significance of honeybees has overshadowed other insect pollinators, taxonomic impediment, limited investment in entomological training, and insect systematics. In many cases, Diptera species are classified into generic “Diptera” groups in ecological datasets without species-level identification, thereby limiting ecological insights.

Strikingly, Diptera species serve as emblems in many ways. Religiously, Diptera species served several symbolic roles. In Christianity, for example, demonology, Beelzebub is a demonic figure, the Lord of the flies, and the God of the Philistines. Furthermore, Courtney et al. (2017) added that Diptera species are regarded as the icon of genetic research. For instance, about a century ago, *D. melanogaster* was introduced as a laboratory animal for geneticists, and it is now the icon of genetic research. Diptera species in ancient Egypt represented tenacity and courage (Kenawy & Abdel-Hamid, 2015). Furthermore, it is thought that the fly in Egyptian mythology gave protection against diseases or misfortunes (Kenawy & Abdel-Hamid, 2015). The mentioned importance (cultural and religious) of Diptera accentuates a deep-rooted human appreciation of these species. Hence, conserving these species goes beyond the ecological value. It represents the preservation of cultural heritage and identity embedded within specific ethnic groups of people.

2.4 Challenges to AD research

The Afrotropical region, formerly known as the Ethiopian region, is considered one of the most biodiverse areas globally, yet it remains understudied, particularly regarding Diptera species. The order Diptera is one of the most species-rich insect orders, yet its diversity in many parts of the Afrotropical region is poorly documented (Kirk-Spriggs & Sinclair, 2017). To a larger extent, this is due to a lack of dipterists, funding, support, and inadequate technology for taxonomy (Coetzee et al., 2021).

Lack of taxonomists is a shared problem amongst entomologists. Coetzer & Eardley (2019) noted that there are only four taxonomists for bees, three based in South Africa (Brauns, Whitehead, and Eardley), and Paul is based in Belgium. The case is no different for the Diptera species. Jordaens et al. (2024) noted that a lack of Diptera taxonomic experts and collection curators from the Afrotropical Region (except for South Africa, perhaps) has contributed to the understudied nature of Diptera species. As such, a training course has been designed for the training of young and emerging entomologists in the Afrotropical Region, prompted by the Royal Museum for Central Africa (Jordaens et al., 2024). Other training courses have been put forward for the identification of Tephritidae in the region. These include training organized by the Southern African Development Community (SADC), FAO/International Atomic Energy Agency (IAEA) training courses in Benin, R´eunion Is., Kenya, and Mauritius, among others (Jordaens et al., 2024). This lack of taxonomic capacity has contributed to a lack of Diptera inventories and data deficits. Apart from mobilizing resources for the training of young taxonomists, more funding should be channeled towards creating systems that will assist in the identification of Diptera species faster to meet the global Taxonomy Initiative (GTI) and Conventional on Biodiversity (CBD) goals.

2.5 Global and regional efforts in taxonomic capacity building

To redress the global 'taxonomic impediment,' the Global Taxonomy Initiative (GTI) was put forward under the Convention on Biological Diversity (CBD). The GTI aims to facilitate species discovery before extinction, promote data-sharing, and build taxonomic capacity in biodiversity-rich but resource-constrained countries/regions. Unfortunately, several countries in the region have struggled to align with GTI goals due to infrastructural and economic constraints (CBD, 2020).

Molecular techniques such as DNA barcoding and environmental DNA (eDNA) are on the rise to try and solve these impediments (Ekesi et al., 2016; Jordaens et al., 2015; Ochieng et al., 2019; Heo et al., 2020; Ricarte et al., 2020; van Klink et al., 2022). Molecular techniques have facilitated Diptera taxonomy by enabling species identification from genetic material. A study by Ruiz-Arrondo et al. (2018) assessed the use of the *cox1* DNA barcoding region for the identification of Diptera species of blackflies in Spain, and the results indicated that combining DNA barcoding with morphology enhanced the taxonomic rationale in identifying blackflies. Similarly, Kamdem et al. (2023) used the mitochondrial cytochrome-c oxidase subunit I gene (COI) to determine the hoverflies of Free State in South Africa and managed to record 15 nominal species from nine genera, of these species, five had not been previously reported to occur in South Africa. These amazing results are a testament to the potential of molecular techniques in revolutionizing Diptera identification. However, a study by Meier et al. (2006) noted a relatively low success rate of <70%. Misidentifications were due to the overlap between intra- and interspecific genetic variability, which contributed 6.5% of all query sequences to have allospecific (3.6%) best-matching barcodes. They also found out that 21% of 449 Diptera species lacked unique barcodes when consensus sequences of all conspecific sequences were used. Kamdem et al. (2023) noted that within the 78 specimens analyzed, the automatic partitioning (ASAP) estimated 14 – 17 species, yet the Poisson tree based on MPTP and SPTP models estimated 15 and 16 species. They went on to recommend the necessity of using different species delimitation models in DNA barcoding for species diagnoses. Although these techniques have proved to be powerful, sophisticated laboratories are needed, yet they are not always available in resource-limited countries like Zimbabwe. Thus, making the process more expensive for developing countries, as they need to constantly send their specimens to developed countries for sequencing. This, therefore, leaves a handful of scientists to do the job rather than having more scientists working on diptera research.

2.6 Machine learning models

Among the machine learning (ML) models that exist, in this section literature was reviewed on the supervised learning models using Google Teachable Machine. The models have proved to be effective in a number of ways. For instance, a study by Gupta & Homchan (2021) developed an ML model for *A. domesticus* and *G. bimaculatus* species classification and sexing and achieved 100% accuracy. Additionally, GTM was used to train a model for the classification of *A. aegypti* (Linnaeus) and *A. albopictus* (Skuse) Ong & Ahmad (2022) and achieved a high accuracy rate of 92.56%. Moreover, Park et al. (2020), with a dataset of 3600 images, acquired an accuracy rate of 97%. The power of this newly introduced web-based GTM cannot be ignored in species identification, especially in a time when the traditional identification methods are insufficient, inaccessible, and tedious. Mobile applications have become alternatives alongside molecular techniques. For instance, platforms like iNaturalist and PlantNet integrate deep learning for real-time species recognition (Horn et al., 2018). There is therefore a need to develop locally based mobile applications for species identification rather than relying on externally trained models.

2.7 Evolutionary history of machine learning (ML)

Machine learning (ML) was formally proposed by Arthur Samuel in 1959 at IBM, defining it as the study that enables computers to learn without being explicitly programmed (Savitha et al., 2023). The foundations of ML date back to 1943 when Warren McCulloch and Walter Pitts created the first neural network with electric circuits, demonstrating that machines could communicate without human involvement. In 1950, Alan Turing introduced the Turing Test to assess whether a machine could convincingly mimic human behavior (Savitha et al., 2023). Shortly after, in 1952, Arthur Samuel developed the first high-level computer program to play checkers using alpha-beta pruning, marking a pioneering practical application of ML (Savitha et al., 2023). In 1957, Frank Rosenblatt introduced the perceptron, an early artificial neural network that became foundational to modern ML methods (Savitha et al., 2023). The nearest neighbor algorithm emerged in 1967 to automatically detect patterns and similarities within large datasets (Savitha et al., 2023). Backpropagation, developed in 1974, enhanced neural network learning by adjusting weights to improve predictive accuracy. By 1979, the Stanford Cart became the first autonomous robot capable of navigating a room full of obstacles without human intervention, demonstrating the practical potential of machine learning in robotics (Savitha et al., 2023).

Therefore, the most promising power of ML risks failure if no one utilizes them, especially in biodiversity conservation, where the current methods are not sufficient to monitor wildlife species, let alone insects. The recently introduced web-based ML (GTM) platform offers tremendous opportunities for ecologists and conservationists to train models that will assist in species identification, monitoring, and diagnosis. What makes a digital tool feel usable, useful, or trustworthy in a context like Zimbabwe, where infrastructure may vary and access to expertise is uneven? This was further cemented by Vinuesa et al. (2020), who argued that the use of machine learning can help achieve 134 targets of the UN 2030 Agenda for Sustainable Development goals, a considerable contribution despite potential hindrance in 59 other targets, should the technology go unregulated.

2.8 Citizen science applications and SDG relevance

Mobile tools can also support participatory science, where non-specialists contribute biodiversity data. Citizen science initiatives have proven effective in increasing ecological monitoring capacity, especially where institutional coverage is limited (Bonney et al., 2014). Such efforts align with SDGs 15 (Life on Land), 13 (Climate Action), and 4 (Quality Education). Applications that engage local communities in Diptera monitoring can enhance awareness, data collection, and conservation outcomes. Hence, the mobile interface must be user-friendly to accommodate citizen scientists.

2.9 Theories

This research has been supported by several theories, including taxonomic impediment, diffusion of innovation theory, participatory science/citizen science, niche theory, and habitat heterogeneity theory.

2.9.1 Taxonomic impediment

This concept assumes that taxonomic studies are insufficient in number, breadth, and speed of publication (Evenhuis et al., 2007; Raposo et al., 2021; Yawson et al., 2004), and are unable to meet the demands of conservationists and society, given the onset of a massive new extinction event. Under this scenario, it is believed that taxonomists will be unable to fill this gap, that is, to name all of the planet's extant species before they become extinct (Rognes, 2011, 2013). Therefore, there is a need to develop new technologies to facilitate species identification before they go extinct. The smartphones people carry around in conjunction with machine learning can be used to identify species and document the extant biota on the brink of extinction.

2.9.2 Participatory science/citizen science

This theory offers participatory approaches to science communication (Giardullo et al., 2023). This theory is developed to promote public participation and public engagement, shifting the paradigm from public understanding of science to a more integrated framework (Giardullo et al., 2023). Therefore, tools that allow citizen scientists to participate are needed. Platforms such as iNaturalist have proven to be effective in allowing citizen scientists to upload pictures of the observed species. Such tools are needed for insect orders like Diptera. Platforms like iNaturalist have proven to help scientists from all walks of life connect and collaborate.

2.9.3 Habitat heterogeneity theory

The theory suggests that diverse habitats create various niches. Each environmental pocket is defined by light availability, vegetation structure, soil type, or microclimate and offers a unique ecological opportunity (Zellweger et al., 2019). This theory has been supported by several studies noting the importance of habitat structure/type in shaping insect communities (Crisp & Lloyd, 1954; Pollet, 2001; Tarakini et al., 2021). Several studies have indicated that different habitat types, such as grasslands, forests, and wetlands, influence distinct Diptera communities, with more heterogeneous environments hosting higher species richness compared to homogeneous environments (Stein et al., 2014; Vezenegho et al., 2009). Research has demonstrated that areas with various vegetation types, like the Amazon Forest and Cerrado, harbor a higher richness of necrophagous flies compared to more homogeneous habitats like Mangroves (Pereira De Sousa et al., 2016). Additionally, Mulieri et al. (2022) discovered that Sarcophagidae abundance was highest in grasslands, yet the lowest abundance was recorded in forests. They also discovered more than 15 species in grasslands, out of the 17 species discovered during their study. However, a study by Ricarte et al. (2011) discovered the highest species richness of Syrphidae in woodland sites. These disparities may mean that different species prefer different habitats. As such, Diptera sampling should cover every habitat type in the study area sites. Different species occupy different niches in an ecosystem. This theory offers an elegant lens to view Diptera species variation across habitats.

2.10 Limitations of the identification tools

The proposed molecular tools are highly sophisticated and expensive, yet this might also add to the existing taxonomic impediments in the Afrotropical region. Despite the potential of mobile and artificial intelligence (AI) technologies in species identification, limitations exist. The accuracy of image-based classifiers depends on high-quality, annotated training data, which is often lacking for AD. Internet access and smartphone penetration are still uneven in rural areas, which may affect deployment. Moreover, many fly species are cryptic and morphologically similar, posing challenges for image recognition systems (Cromwell et al., 2021; Sapkota et al., 2020). These might be difficult to work with when working with minute Diptera species.

2.11 Chapter summary

This chapter has succeeded in demonstrating the taxonomic impediments, taxonomic developments and the integration of mobile technology and machine learning into species identification is a promising development, especially for regions where traditional taxonomic resources are scarce. The next chapter will start off with a systematic review to review literature on; taxonomic developments, distribution, endemism, and economic impact of Afrotropical Diptera: a systematic review.

Chapter 3

Taxonomic developments, distribution, endemism, and economic impact of Afrotropical Diptera: a systematic review

3.1 Context

The aim is to investigate the taxonomic developments (revisions, molecular tools, and machine learning), distribution (species occurrence), endemism, and economic effects of Diptera species across the 7 sub-Afrotropical regions. This study used the conceptual framework as outlined in Fig. 3.1.

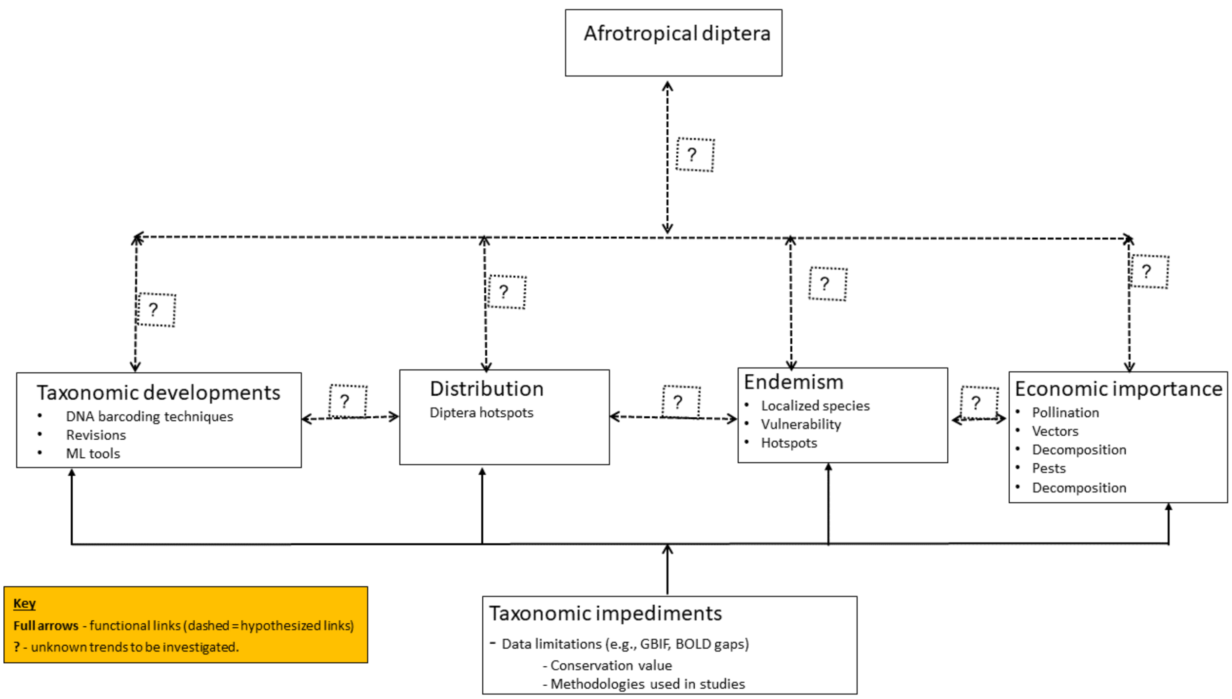

Fig. 3.1: The conceptual framework used review of the taxonomic developments, distribution, endemism, and economic impact of AD. **AD** =Afrotropical Diptera.

3.1 Abstract

The identification of AD remains fairly underdeveloped, mainly because of the scarcity of taxonomic experts and collection curators. Only species of economic importance, like Fruit flies (Tephritidae), Mosquitoes (Culicidae), Hoverflies (Syrphidae), and Tsetse flies (Glossinidae), have received more attention from scientists, leaving other species less explored. This review aimed to determine the taxonomy developments, distribution, endemism, and economic impact of AD species. To achieve this, literature was searched in the Web of Science (WOS) and Scopus to gather data on the 108 AD families. A total of 2027 genera were collected from the literature, belonging to the 108 AD families. Of the reviewed AD families, family-level morphological identification keys are present, but there are gaps in keys that distinguish species for some families. However, molecular technique publications (87.2% of the articles included) and machine learning techniques are slowly gaining traction, with groups of veterinary, agricultural, and medical importance experimenting with these techniques more. Of the AD families under review, South Africa had the highest number (84.3%), while the Mascarene Islands had the least (1.9%). Similarly, South Africa harbored the most endemic genera (20.8%), but countries in West Africa (e.g., Benin (0.2%), Burkina Faso (0.2%)) and the Southern Peninsula had the least, among other countries. Of the 132 studies included in this review, 17% were conducted in South Africa, followed by Kenya with 14%. In sharp contrast, the least number of studies were conducted in islands such as Cape Verde, accounting for only 0.8%. Notably, Diptera species play pivotal roles as parasites, pests, pollinators, and biological control agents across Southern, Eastern, and Central Africa. This study highlights that despite the progress made in developing the keys, the process of identification is still laborious and needs specialized skills. The emerging molecular and computer vision techniques have the potential to revolutionize the identification of AD species.

Key words: Afrotropical Diptera, economic significance, endemism, identification keys, distribution

3.2 Introduction

The dipteran fauna is one of the insect world's most captivating and diverse groups. The order has over 160,000 described species among approximately 10,000 genera representing 160 families of Diptera (Kirk-Spriggs & Sinclair, 2021). The order constitutes 15% of the world's known insect species, with indications suggesting that the number of species could be higher (Borkent et al., 2018; Courtney et al., 2017; Pape et al., 2011). Of the 160,000 described species in the world, the

[1] This chapter is a manuscript in preparation for the African Journal of Ecology with the following details: Matengo T., Musundire R., Gugulethu T., and Tarakini T. (**Submitted in PLOS One**). A systematic review of the taxonomic developments, distribution, endemism, and economic impact of Afrotropical diptera.

percentage contribution of the Palaearctic, Neotropical, Oriental, Nearctic, Afrotropical, and Australasian regions is 27%, 20%, 14%, 14%, 13%, and 12%, respectively (Berrones-Morales et al., 2020; Grootaert, 2009; Kirk-Spriggs & Sinclair, 2017; Kirk-Spriggs & Stuckenberg, 2009; Li et al., 2019; Tephritidae & Herren, 2019). All these regions are considered understudied (Alzahrani et al., 2025; Hennig, 1973). Therefore, research that focuses on the taxonomy of Diptera and the training of new dipterists has become critical globally.

The Afrotropical region, initially referred to as the Ethiopian region by Sclater in 1858, stretches south of the Sahara in Africa, the southern Arabian Peninsula, Madagascar, and the West Indian Ocean Islands and it designates a unique eco-zone characterized by varied flora, fauna, and climate (Musundire et al., 2011a). The region harbors 108 Diptera families accounting for approximately 20,000 species (Kirk-Spriggs & Muller, 2017), and these play important roles in pollination, decomposition, and as vectors of diseases. Despite their pervasive and ecological significance, the systematics and taxonomy of AD remain fairly underdeveloped, and this has been hindering research, leading to gaps in our understanding of their biodiversity and economic impacts.

The development and availability of identification keys for AD species are essential for improving research and conservation efforts, yet many Diptera species lack updated and accessible identification keys (Courtney et al., 2017). The dwindling taxonomic expertise, coupled with the need to ease the identification process, has led to the evolution of molecular techniques (Jordaens et al., 2015; Ogola et al., 2023; Valley et al., 2019). Different molecular techniques like the PCR and DNA barcoding (Jordaens et al., 2015; Onah et al., 2017; Snyman, 2021), have proved effective in separating species that were difficult to separate morphologically. However, the molecular technique relies on specialized laboratories, skilled personnel, and constant funding for sequencing and analysis (Frewin, 2015), which is constantly lacking in resource-limited countries like sub-Saharan African countries. Another technique harnessed towards easing the identification of AD species is the power of ML (Gao et al., 2024; Odabas & Kaya, 2024). Studies using machine learning have utilized wing interference patterns (WIPs) (Cannet et al., 2023), mid-infrared spectra obtained by scanning the heads and thoraces of the mosquitoes using an attenuated total reflection fourier transform infrared (ATR–FT-IR) spectrometer (Mwanga et al., 2024). Technological advancements are also making it possible to grade the ages of mosquitoes. For instance, near-infrared spectroscopy (NIRS) has led to mosquito age grading (Milali et al., 2019). However, machine learning has been limited by low data sets. If harnessed properly, it can help ease the identification process alongside molecular techniques.

Dipteran fauna distribution has been affected by climate, habitat loss, and human activities (Engels et al., 2020). Furthermore, these threats will worsen with climate change being projected to increase by 2050, thereby exposing Diptera habitats to floods and droughts (Parvez et al., 2023). The effects of urbanization and agriculture are looming and modifying habitats, making them unfavorable to Diptera species (Laurito & Arias-Alzate, 2024). In this fast-changing environment, assessing Diptera distribution is crucial. As climate change and human-induced threats can cause local extinctions of Diptera species, stressing the need for opportune research (Wouters et al., 2024). As such, understanding the distribution of AD species is important as conservation efforts are hinged on such information.

Endemism is an equally important factor in biodiversity conservation. Endemic species are more prone to extinction because of their limited distribution compared to widely distributed species (Manes et al., 2021). Kirk-Spriggs & Muller (2017) reported that the AR is home to four endemic Diptera families: Glossinidae (tsetse flies), Marginidae (margin flies), Mormotomyiidae (fruit hairy flies), and Natalimyzidae (antler flies). Furthermore, AD species show higher levels of endemism compared to other insect groups. For instance, work by Santos & Ribeiro (2022) showed that craneflies (family: Tipulidae) have higher levels of endemicity rates than vertebrates and butterflies. Santos and Ribeiro added that 93% of Tipulidae species are endemic to biogeographical sub-regions, while 84% are endemic to their respective dominions (Santos & Ribeiro, 2022). As such, research in this regard must explore other AD families, check their endemicity rates, and assess potential threats that might dwindle populations of such species.

Studies in the past have shown the economic impacts of AD in the region. These studies have been driven by the need to reduce the impacts of AD species on human health and agriculture. Coetzee (2014) demonstrated the role played by Diptera species as vectors for several human and animal diseases, causing difficult challenges to public and animal health (Coetzee, 2014). For instance, Culicidae (e.g., *Anopheles*) and Glossinidae (e.g., *Trypanosoma)* are responsible for diseases such as malaria and sleeping sickness, respectively (Liu et al., 2022; Mweempwa et al., 2021) as noted in 2020. African countries suffered the most from malaria, with the largest number of malaria cases (64.7 million) and more than 150,000 deaths observed in Nigeria alone (Oboh et al., 2018).

Furthermore, house flies have been caught up in the spread of cholera in Zimbabwe during outbreaks of 2008, 2018, 2019, and 2024 (Anderer, 2024). For instance, the outbreak declared over in May 2009 resulted in 98,592 cases and 4288 deaths. Psychodidae negatively affect livestock and wildlife through blood loss and irritation caused by the bites of adult Phlebotominae species (Lehane & Lehane, 1991; Munstermann, 2019). Moreover, livestock also suffer from diseases such as leishmaniasis and vesicular stomatitis, which are spread by Phlebotomines (Harris, 2017). All these unfortunate scenarios are happening amidst a taxonomic crisis hindering AD research.

Dipterous pests, especially those from the family Tephritidae, cause significant threats to crops in Africa. The menace of fruit flies to the horticulture industry in Africa is unbearable, yet fruit and vegetable production is one of the fastest-growing sectors of agriculture, contributing to food security and poverty eradication (Billah et al., 2015; Hawkes et al., 2024). For instance, *C. capitata* (medfly) is one of the most important worldwide threats to fresh fruits (Liang, 2011; Qin et al., 2015) and can infest from 250 to 400 fruits tree species. Furthermore, the species was estimated to cause US$242 million/year in economic losses in Brazil (Liu et al., 2022; Oliveira et al., 2015). Despite the looming impacts of Tephritidae, there is little knowledge amongst stakeholders about the fruit fly pests regarding their pest status, economic impact, and control measures (Billah et al., 2015; Mulungu et al., 2023). Tephritidae cause economic losses to fruit and vegetable crops and have quarantine implications. Numerous studies with different research interests have been conducted on fruit flies throughout the African continent. Despite these studies, there is little knowledge among stakeholders about fruit fly pests in terms of the economically important species, their pest status, economic impact, and control strategies. Agromyzid larvae, on the other hand, known as leaf miners, create distinctive galleries in leaf parenchyma, causing damage to various plant parts, including leaves, stems, flowers, and fruits (Marchiori, 2022). These pests show polyphagous feeding habits, impacting a wide range of plants, especially *Solanaceous* crops. The damage posed by leaf miners jeopardizes plant health and crop yields, necessitating effective management strategies. Hence, understanding the bio-ecology, life cycle, and distribution of agricultural pests is crucial for developing comprehensive pest management strategies to mitigate their impact on agricultural systems.

Despite the negative impacts of Diptera species that cannot be ignored, AD species have also been known to be important pollinators, decomposers, food for humans, and fodder for other animals

(Abajue, 2023; Gbarakoro & Abajue, 2022). For instance, Syrphidae are considered the second most important group of pollinators after wild bees (Dawah et al., 2020; Li et al., 2023). Syrphids commonly forage on both wild plants and crops, where they provide pollination and biological control services (Li et al., 2023), and the value of hoverfly-mediated pollination has been valued at USD300 billion per year globally (FAO, 2017; Li et al., 2023). Furthermore, the black-soldier fly (*H. illucens*) full-fat larvae, a decomposer, is being used as an alternative to fish feed, and the feed has proved to be effective, contributing to food security and poverty alleviation (Devic et al., 2018; Harun et al., 2021).

Despite their negative impacts that cannot be ignored, AD species remain understudied. Therefore, there is a pressing need for knowledge transfer and training of young and emerging dipterists. This work therefore, intended to (i) analyze the taxonomic developments in AD species, (ii) assess the distribution of Diptera species across the Afrotropical region, (iii) assess the endemism of AD genera and species, and (iv) describe the documented uses of AD. By addressing these knowledge gaps, this study will expose taxonomic gaps, areas of endemism, and the economic significance of AD.

3.3 Methods

3.3.1 Data collection

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and checklists for literature review (Page et al., 2021), an extensive literature search was conducted from the 10th of January to the 1st of February 2024 from the Web of Science (WOS) and Scopus under Chinhoyi University of Technology (CUT). The following search string was initially tested then used to search for literature: ("Diptera*" OR "true flies*") AND ("Afrotropical*" OR "sub-Saharan Africa*") AND ("identification*" OR "taxonomy*" OR "systematics*" OR "identification keys*" OR "taxonomic keys*") AND ("taxonomic revisions*" OR "DNA barcoding*" OR "molecular identification*" OR "machine learning*" OR "artificial intelligence*" OR "computer vision*") AND ("endemism*" OR "economic importance*" OR "economic significance*" OR "distribution*"). It is worth mentioning that this review also benefited from gleaning in literature sources covered in the comprehensive Manuals of Afrotropical Diptera (volumes 1 to 3), which were published by Kirk-Spriggs and Sinclair (2017a; 20217b; 2021).

The search was limited to studies done in the AR between 2000 – 2024. This period comprised of recent findings with significant methodological developments, including DNA barcoding, ML, and AI that are most relevant for conservation planning, habitat management, and policy decisions in the AR). The study included articles published in English, in the AR, and studies that reached the final stage of publication. Information on the distribution, endemism, and economic impact of the reviewed literature is summarized in the three volumes of the Manual of Afrotropical Diptera (Kirk-Spriggs & Sinclair, 2017a; 20217b; 2021). The titles and abstracts were screened using Rayyan Artificial Intelligence (AI) tools (https://new.rayyan.ai/reviews/1446716/screening) to retain only the records that were relevant to the review. Full-text screening was done manually to exclude studies that did not include the major themes of the review. The inclusion criteria compromised studies that were published in the English language and which covered: (i) taxonomic developments within the order (ii) economic significance/importance for each Diptera family, (iii) the distribution of Diptera species in the AR, and (iv) whether or not the genus is endemic to a particular country/sub-Afrotropical region. The relevant articles were imported, organized, and stored in Mendeley reference software. The PRISMA flow chart of the literature-searching process is illustrated in Fig. 1. The themes that resulted from the keywords and titles from the WOS searches were gathered. All the obtained data for these AD were captured in Excel worksheets for analysis.

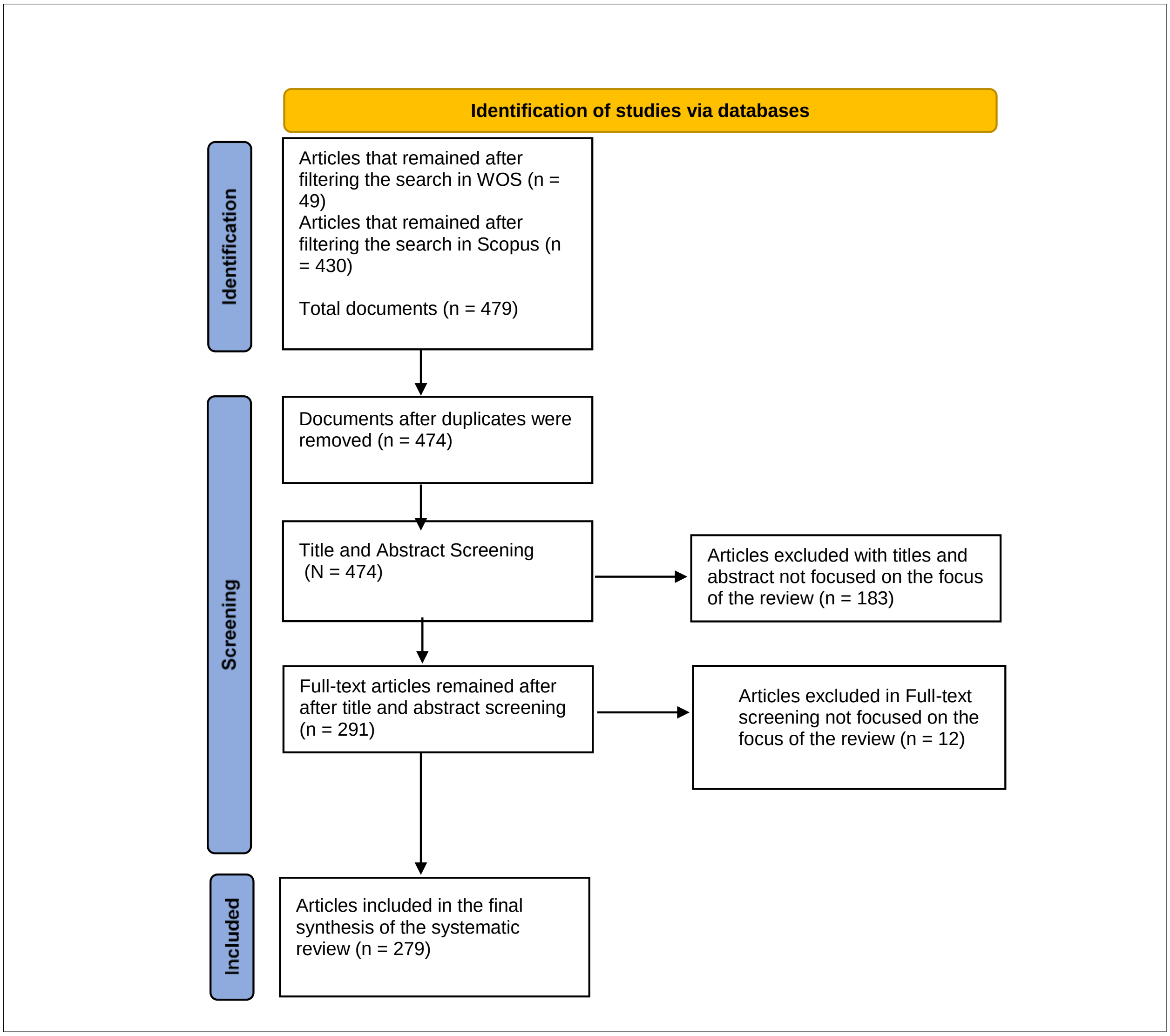

Fig. 3.2: PRISMA Flow chart illustrating the literature gathering process from the Web of Science and Scopus between 2000 - 2024. **PRISMA** = Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

3.4 Data analysis

The taxonomic developments were re-categorized into broad classes (i.e., taxonomic review, revisions, molecular techniques, and machine learning). As the focus of this study was on the Afrotropical region, the countries in which each genus was recorded were categorized into seven sub-regions following Crosskey (Crosskey et al., 1980) as Southern Africa, Indian Ocean Islands, Central Africa, Atlantic Ocean Islands, Southern Arabian Peninsula, East Africa, and West Africa.

Heat maps showing the number of AD families per country were created using the "ggplot2" (Wickham, 2016) and "sf" (Pebesma & Bivand, 2023) in the R language for Statistical Computing (Team, 2024). A compound graph was used to show the compositions of endemism per region.

To explore the relationship between the AD families' economic significance and the Afrotropical sub-regions, a Principal Component Analysis (PCA) was used. Furthermore, VOSviewer (version 1.6.20, https://www.vosviewer.com/) was used to extract keywords from literature on the focus of this review (i.e., taxonomy, distribution, endemism, and economic importance). A bibliometric analysis using VOSviewer revealed key thematic clusters within the literature. The co-occurrence of keywords from literature in which the size of nodes indicates the frequency of occurrence, and the curves between the nodes represent their co-occurrence in the same publication. The themes that resulted from the keywords and titles from the literature review were plotted using bibliometric analysis in VOSviewer. Bibliometric analysis using VOSviewer with a threshold frequency of three revealed key thematic clusters within the literature.

Chi-squared tests were also used to investigate: (i) if there was any association between levels of endemism across the Afrotropical sub-regions, (ii) the relationship between the recorded number of genera and species in each country.

3.5 Results

A total of 2,027 genera of Diptera were recorded in this literature review. Out of these genera, 36.9% (n = 804) were endemic to the Afrotropical region. The sizes of the families ranged from 1 to 164 genera. The Manual of Afrotropical Diptera provides morphological family-level identification keys of the 108 families, volume 1: Chapter 12. The line graph in Fig 2 illustrates the number of publications published each year between 2000 and 2025 about the taxonomic developments, distribution, endemism, and economic impact. The data points show that the number of publications varies per year. During the first phase, from 2000 until 2006, the annual numbers of publications were generally below ten. The numbers started to increase in the year 2008, with the highest peaks in 2021 and 2023 in which 45 publications were found.

3.6 Publications on the taxonomic developments

Fig. 3.3. illustrates disparities in publications focused on taxonomic developments. Out of the 279 included articles, 47.7% addressed the taxonomic developments on AD species, with Nigeria

holding the highest percentage (22.6%), followed by South Africa with 14.8%. The least contributing countries, including Zambia, Zimbabwe, and Rwanda, had less than 2%. Amongst the 47.7% that demonstrated the taxonomic developments, 87.2% employed molecular techniques for species identification. The Culicidae (58.62%), Glossinidae (16.38%), Tephritidae (5.7%), and Syrphidae (3.45%) were the most explored families. Moreover, Asilidae, Oestridae, and Ulidiidae less received attention with 0.86% each, as illustrated in Table 2 in Appendix i.

3.7 The number of the recorded Diptera families in the Afrotropical region

Of the 108 AD families under review, South Africa (84%) had the highest number of Diptera families, while the Mascarene Islands had the least number (7%), as shown in Fig. 3.4.

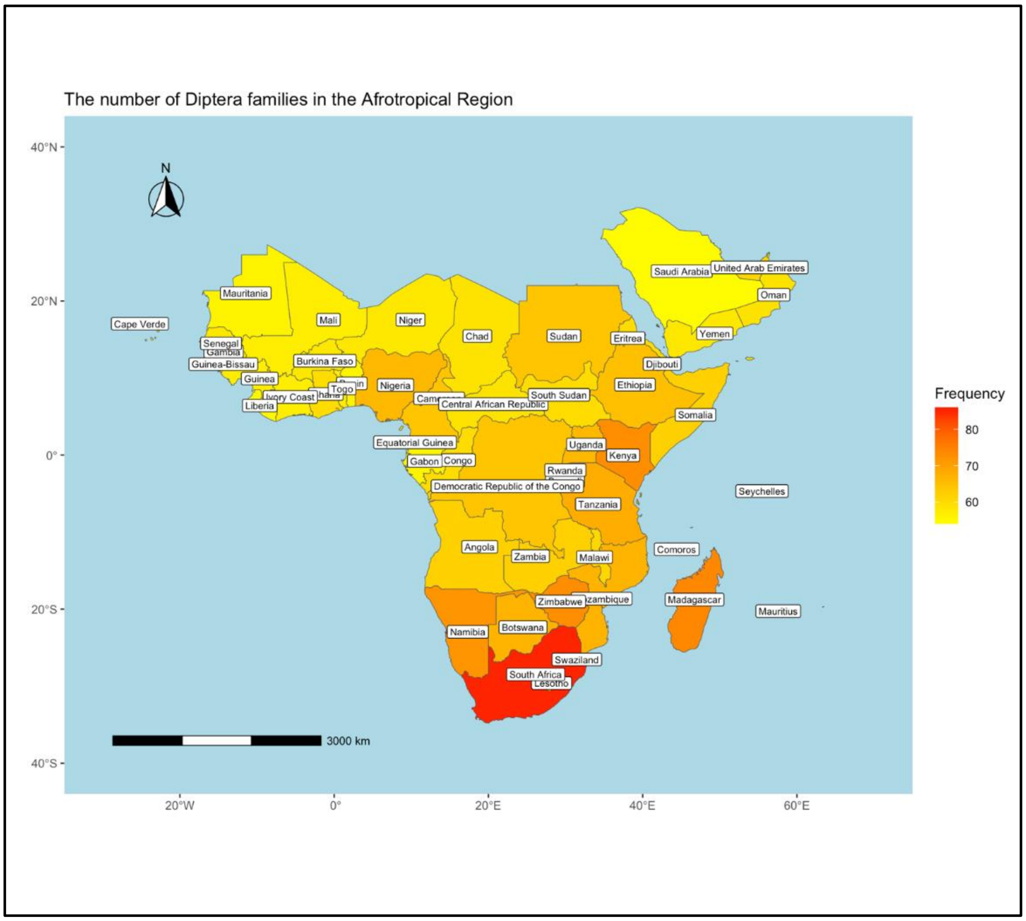

Fig. 3.4: Number of recorded AD families in countries in the Afrotropical region. **AD** = Afrotropical Diptera.

3.8 Endemic genera in the Afrotropical region

Of the 2,027 genera under review, 804 were endemic and were recorded in 40 countries. Of the 804, South Africa had the highest number of endemic genera (20.8%), while the least number was recorded in countries like Benin (0.1%), as illustrated in (Appendix 1; Table 2).

Table 3.1: The number of reviewed endemic genera in Afrotropical countries.

Name of countries	**Number of Endemic Genera**	**Percentage %**
Angola	40	5
Benin	1	0.1
Bioko Is	4	0.5
Botswana	86	10.7
Burkina Faso	1	0.1
Burundi	45	5.6
Cabo Verde	1	0.1
Cameroon	29	3.6
Chad	1	0.1
Comoros	7	0.9
Côte d’Ivoire	8	1
DRC	52	6.5
Equatorial Guinea	5	0.6
Eritrea	2	0.2
Ethiopia	20	2.5
Gabon	1	0.1
Gambia	1	0.1
Ghana	10	1.2
Guinea	3	0.4
Kenya	47	5.8
Lesotho	11	1.4
Liberia	2	0.2
Madagascar	74	9.2
Malawi	10	1.2
Mali	1	0.1
Mauritius	2	0.2
Mozambique	18	2.2
Namibia	60	7.5
Nigeria	20	2.5
Reunion Is	1	0.1
Rwanda	2	0.2
Saudi Arabia	1	0.1
Senegal	2	0.2
Seychelles	8	1
Sierra Leone	3	0.4
Somalia	3	0.4
South Africa	167	20.8

Tanzania	25	3.1
Togo	1	0.1
Uganda	13	1.6
Yemen	2	0.2
Zambia	1	0.1
Zimbabwe	11	1.4

3.9 The composition of endemic genera across the sub-region

The Chi-square result showed that, there was a significant association of the endemism levels with faunal sub-region ($p = 0.0001$), in which Southern Africa had the highest number of genera (both endemic and non-endemic ones), whereas the Southern Arabian Peninsula had the least, as shown in Fig. 3.5.

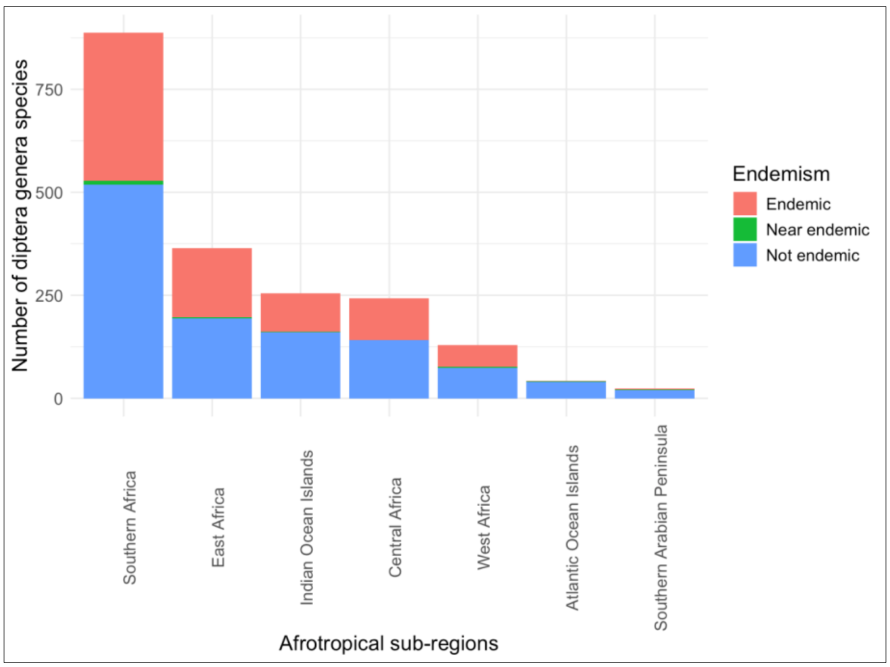

Fig. 3.5: Illustrates the proportions of levels of endemism across the Afrotropical Sub-region (ASR).

3.10 Co-occurrence of AD key words

Of the 3794 words that appeared in the keywords, 424 met the threshold frequency of five. The keywords that appeared most were "Malaria" (total link strength = 110), "*Anopheles*" (total link strength = 109), "Polymerase chain reaction" (total link strength = 82), and "parasitology" (total link strength = 67). The word Malaria was mostly associated with concepts on anopheles, polymerase chain reaction, gene mutation, disease carrier, as illustrated in Fig 3.6.

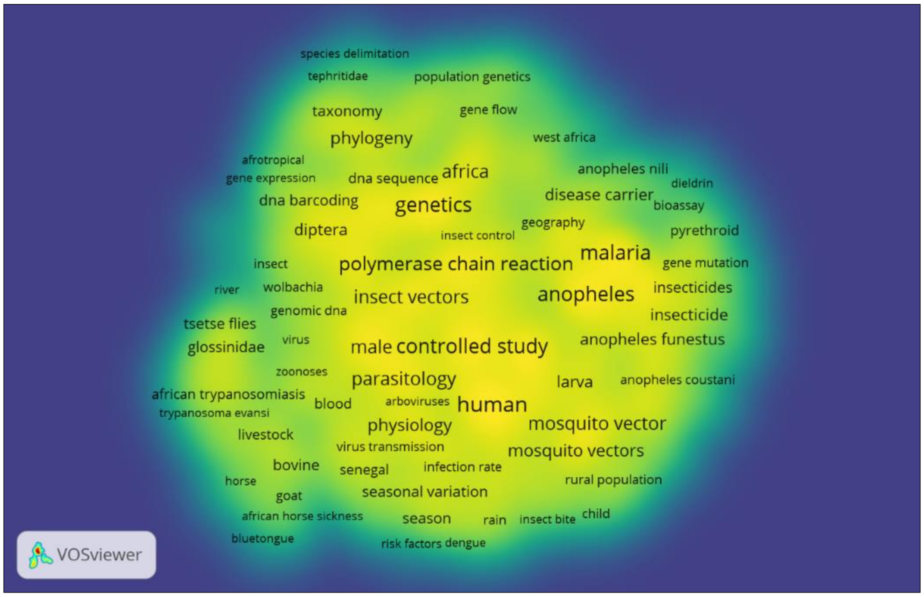

Fig. 3.6: A schematic presentation of the co-occurrence of keywords from literature on AD from the Web of Science (WOS). **AD** = Afrotropical Diptera.

3.11 The use of Diptera genera across the Afrotropical sub-regions

The PCA revealed significant variation in the uses of the Diptera across the Afrotropical sub-regions. Component 1 of the PCA explained 51.7% while component 2 explained 34.3% of the variation in the data. The use of Diptera genera as fish food was cited more in studies conducted in the Indian Ocean Islands, while those conducted in Southern Africa and East Africa focused on vectors, pests, predators, parasites, and the flies as nuisance organisms. The use of Diptera as food was mostly cited in West African studies, while decomposition uses were pronounced more in the Southern Africa sub-region, as shown in Fig. 3.7.

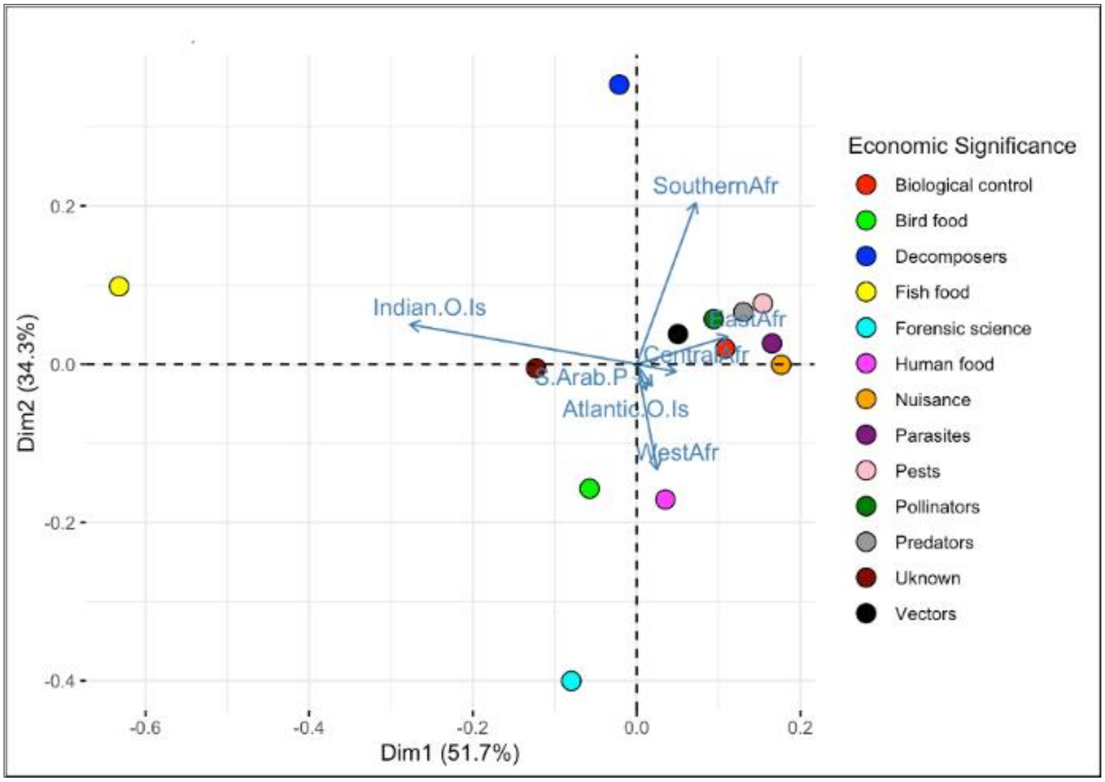

Fig. 3.7: Principal Component Analysis (PCA) results showing the variation of the economic significance of Diptera species across the seven Afrotropical sub-regions. **WstAfr** = West Africa, **AtlanticOIs** = Atlantic Ocean **Islands, S.Arab.P** = South Arabian Peninsula, **SouthernAfr** = Southern Africa, **IndianOIs** = Indian Ocean Islands, **CentralAfr** = Central Africa, **EastAfr** = East Africa.

3.12 Discussion

Over the period between the years 2000 – 2024, research on the taxonomic developments, endemism, and economic impact of Diptera has shown a gradual increase. This upward trend points to the growing concern to solve the taxonomic impediments that have troubled scientists for centuries.

During this study, South Africa emerged as the country with the highest number of publications, AD families, and endemic genera. This can be attributed to the fact that more taxonomic studies have been carried out in these countries compared to others Kirk-Spriggs & Stuckenberg, 2009). This is further supported by the extensive Diptera material from these countries housed in African and European museums. Moreover, South Africa's ecological complexity, characterized by 24 bioclimatic regions (Conradie, 2012), along with its diverse topography, climate, and flora, has facilitated the radiation of Diptera species. A typical example is the Cape Fold Mountains, which serve as hotspots for dipteran fauna, showing a rich diversity of systematically complex families, including Asilidae, Bombyliidae, Empididae, Limoniidae, Mydidae, Nemestrinidae, Tabanidae, Therevidae, and Vermileonidae (Kirk-Spriggs & Stuckenberg, 2009). Hence, more inventories of dipteran fauna in pristine areas are needed to discover species.

Species identification in Diptera remains a challenge, due to its vast diversity and the ongoing limited taxonomic capacity in the Afrotropical region. These challenges have led to delays or misidentification in taxonomic work. Over the past two decades, research has increasingly focused on revising different Diptera groups (i.e., families and genera) and developing tools to ease the identification process (Abdalla et al., 2018; Jordaens et al., 2015; Ricarte et al., 2020; Sebastiani et al., 2001; Siria et al., 2022; Thomas-Cabianca et al., 2021). This review indicated that molecular techniques are effective and have successfully separated morphologically similar species that were previously difficult to distinguish using traditional keys. Nigeria emerged as the leading country where molecular techniques are being employed, mainly on Culicidae (Habeeb et al., 2021; Kwadha et al., 2021). Similarly, efforts to revise some Diptera families and genera have demonstrated the rediscovery of cryptic species most of the time (Jordaens et al., 2021; Ssymank & Jordaens, 2021), hence the need to revise AD species. Additionally, machine learning techniques have been demonstrated to have the power to automatically identify species from images through image recognition to at least family level and do age grading of Mosquito species (Siria et al., 2022). Similarly, in a move to resuscitate the dipterists pool, a course on the taxonomy and systematics of African pollinating flies at the Sokoine University of Agriculture (Tanzania) to train a young generation of dipterists across Africa (Jordaens et al., 2024). Without these efforts, conservation research will remain limited. In response to the taxonomic impediments, the Global Taxonomy Initiative (GTI) and the International Barcode of Life Consortium (iBOL) under the Convention on Biological Diversity (CBD) support molecular methods, such as DNA barcoding and genome sequencing technologies (Costa & Antunes, 2012; Sandall et al., 2023).

The principal component analysis (PCA) demonstrated the variation of the economic importance of AD across the Afrotropical sub-regions (ASR). The PCA indicated that Southern, Central, and East Africa were correlated to vectors, pollinators, decomposers, biological control, nuisance, parasites, predators, and pests, reflecting challenges related to public health and agricultural practices. However, it also showed fodder, human food, and forensic science being correlated to the Indian Ocean Islands, the Southern Arabian Peninsula, and the Atlantic Ocean Islands, and the Indian Ocean Islands. This rapid urbanization is particularly evident in large cities in West Africa located along coastal floodplains and in densely populated informal settlements. For instance, Nigeria had the highest percentage of the global malaria burden compared to any other country, with 27% of the global estimated cases and 31% of estimated deaths, as well as an estimated 55% of malaria cases in West Africa in 2022. These environments create ideal conditions for *Aedes* spp. mosquitoes, leading to increased human exposure to these vectors and, consequently, a higher risk of arbovirus transmission (Chinula et al., 2018; Doumbe-Belisse et al., 2021).

Tephritidae emerged as the most important agricultural pest during the study. This was expected as Africa is infested with these most destructive Diptera pests. These pests affect mainly fruits and vegetables. These pests can lead to economic losses exceeding billions annually due to their destructive habits and quarantine implications (Heve et al., 2021; Onah et al., 2015). The prevalence of species such as *B. dorsalis* has been documented, with studies indicating that it is the most abundant fruit fly in Central Africa, infesting key crops like mango and guava (Makwarela et al., 2025). Unfortunately, many stakeholders are unaware of the economic importance of these pests, hindering management strategies (Billah et al., 2008; Ekesi et al., 2016). Educating the stakeholders (i.e., farmers) is key. Moreover, leaf-miners (Agromyzidae) cause damage to fruits and vegetables, particularly berries, grapes, and citrus, while leaf-miners feed on leaves, leading to reduced crop yields (Brake & Bächli, 2008; Musundire et al., 2011a; Tsacas et al., 1981).

Unfortunately, literature on the beneficial roles of AD species is scattered because many studies focused on the negative impacts of AD species (CABI/EPPO, 1999; Grout & Stoltz, 2007). Diptera are efficient decomposers; for example, the black soldier fly (Stratiomyidae) has been recognized for its potential in waste management (Lord et al., 1994; Mengual et al., 2020; Musundire et al., 2011b; Sheppard, 1983) and as a biological control agent for invasive species like *L. camara* (Cilliers, 1983; Simelane & Africa, 2019). Furthermore, data on Diptera as pollinators is limited. Studies in the Cape Province of South Africa have noted the role of Diptera as important pollinators alongside Hymenoptera, with Syrphidae being considered the second largest pollinator after bees. Given their ubiquitous presence, further research is essential to investigate the effectiveness of Diptera in pollination, as they are found in diverse environments worldwide.

3.14 Conclusion

This review highlighted significant taxonomic advancements in molecular techniques, especially groups of medical, veterinary, and agricultural importance. However, gaps exist in the application of machine learning in AD species, yet it holds the power to ease the identification process especially for large specimens. Future research in resource-limited countries must focus on harnessing the power of computer vision techniques, as molecular techniques rely on constant funding. These gaps underscore the need for a faster and efficient method of AD species identification. Therefore, more models should be trained and tested to develop mobile applications that can identify species. However, regions like Central West Africa and islands such as the Mascarene Islands remain underexplored, reflecting unequal research efforts. Endemism analysis identified South Africa as a biodiversity hotspot, whereas countries like Benin, Burkina Faso, Zimbabwe, and others in the Southern Peninsula showed minimal endemic representation, emphasizing the disparity in species richness and documentation across the region. Additionally, the documented economic roles of Diptera species include their functions as pests, parasites, pollinators, and biological control agents, demonstrating their ecological and economic importance.

3.15 Chapter summary

This chapter managed to systematically review literature on taxonomic developments, distribution, endemism, and economic impact of AD. It showed that of the 279 studies included in this review, 17% were conducted in South Africa, followed by Kenya. In sharp contrast, the least number of studies were conducted in islands such as Cape Verde and Zimbabwe among others.

Chapter 4

Distribution, composition, and community structure of the Afrotropical Diptera in Matopos National Park, Zimbabwe.

4.1 Context

This study focused on understanding the distribution, composition, and community of Diptera species across seasons. Intensive sampling of Diptera species was carried out in MNP using pan traps (colours: yellow, blue, and white). Sampling was undertaken across three main seasons (cool-dry season, hot-dry, and hot-wet) and habitats (mountains, woodlands, and grasslands) in MNP. In this chapter, the influence of habitat type and seasonality on the distribution, composition, and community structure of Diptera species in MNP was investigated as outlined in Fig. 4.1.

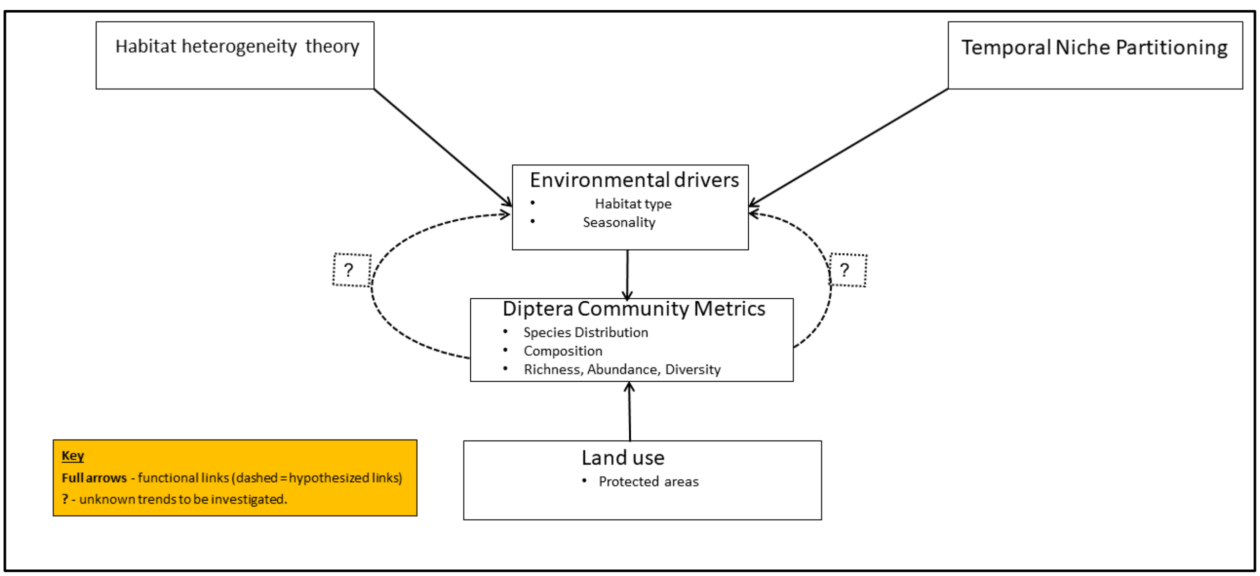

Fig.4.1: The conceptual framework used to assess the distribution, composition, and community structure of the AD in MNP, Zimbabwe. **AD** = Afrotropical Diptera**, MNP** = Matopos National Park.

4.1 Abstract

Although dipteran fauna plays a fundamental role in the ecosystems, little is known about their diversity, richness, and abundance in protected areas in Zimbabwe. MNP in the Southwestern Zimbabwe offers a unique opportunity to study dipteran fauna across different habitats (Mountains (Mt), grasslands (GL), and woodlands (WL)) and seasons (cool-dry (Cd), hot-dry (Hw), and hot-wet (Hw) seasons). Sampling was done from December 2021 to April 2025 (except 2023) using pan traps of three colours (yellow, white, and blue) mixed with a drop of liquid soap resulted in 1838 individuals being collected across habitats and seasons. Of these, 58 species were identified to species level, and 94 genera belonging to 29 Diptera families. The most abundant families were Muscidae (24.15%), while on the contrary, the least families that were collected include the Tephritidae (0.05%). Of the 94 genera collected, were *Minettia* spp. (14.14%), while the least collected genera included *Asarkina* spp. (0.05%). Relative abundance of the 20 most abundant genera revealed *Cosmina* sp as the most abundant genus in Hw, *Minettia* sp dominated the Cd and Hd seasons. *Sarcophaga* sp dominated the GL, while *Minnettia* genus was the most abundant in Mt. Moreover, the best GLM results revealed that species abundance was highest in GL, and Mt, but least in the WL. Furthermore, 2022 had the highest species abundance, but 2025 had the least abundance. Species richness was highest in GL, while lowest in WL. Hw on the other hand had the highest richness, while Hd (Hot-dry) had the least richness. Similarly, 2022 had the highest species richness, while 2025 had the least richness. Regarding the Shannon diversity, GL had the highest diversity, while Mt had the least diversity. Species diversity significantly differed across seasons, with Hd having the highest diversity, while Cd had significantly low species diversity. However, species Shannon diversity varied across years as well, with 2022 having the highest diversity, on the contrary, species Shannon diversity was significantly low in 2024. The logistic regression models revealed that the odds of encountering Anthomyiidae, Muscidae, and Platystomatidae were high during the Cd compared to other seasons, whereas the likelihood of Asilidae, Rhiniidae, and Tabanidae was high in Hw. However, the odds of encountering the family

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[2] This chapter is a manuscript in preparation for PLOS One with the following.

details:

Matengo T, Musundire R, Tarakini G, and Tarakini T (**in preparation**). The distribution, composition, and community structure of the Afrotropical Diptera in Matopos national park, Zimbabwe.

Lauxaniidae were high during the Hd. Furthermore, Asilidae, Bombyliidae, Lauxaniidae were highly encountered in 2024, while Calliphoridae, Platystomatidae in 2021, Rhiniidae in 2025, and Tabanidae, Tachinidae in 2022. Moreover, the odds of encountering Asilidae, Calliphoridae, and Platystomatidae were high in WL compared to other habitats. The likelihood of encountering Anthomyiidae and Lauxaniidae in Mt. However, the odds of encountering Muscidae, Sarcophagidae, Syrphidae, and Tachinidae not vary by habitat, neither did the odds of encountering Sarcophagidae, Syrphidae, Tachinidae varied by season or by vary by year for Muscidae, Sarcophagidae, and Syrphidae.

4.2 Introduction

Insects are at the center of food webs, consumed by birds, bats, small mammals, reptiles, amphibians, spiders, and other insects (Amin et al., 2023). The name "two wings" refers to the fact that the hind pair of wings is significantly modified to halteres. The order Diptera is quite ubiquitous, occupying a lot of continents and populating habitats across seasons (Courtney et al., 2017). The order Diptera is divided into two suborders, namely Nematocera and Brachycera. Diptera species play critical roles as decomposers, pollinators, parasitoids, and vectors for diseases.

The Afrotropical region is home to ~20,350 extant species, described within 108 extant families, in which Asilidae (1,685), Bombyliidae (1,384), Chironomidae (604), and Culicidae (780) are among the most represented families in the region (Kirk-Spriggs & Sinclair, 2017). The region boasts four endemic families (Glossinidae, Marginidae, Mormotomyiidae, and Natalimyzidae, howbeit Glossinidae and Natalimyzidae are known from the fossil records in North America and Europe respectively) are endemic to the Afrotropical region (Kirk-Spriggs & Sinclair, 2017). Furthermore, more Diptera inventories are still needed to discover the 30,000 species that are awaiting description, as noted by Kirk-Spriggs & Sinclair (2017: 2). Hence, research that aims to uncover Diptera diversity along environmental gradients and across seasons is needed to describe these understudied species.

Southern Africa has been noted to be a hotspot for arthropod species, with the Greater Cape Floristic Region (GCFR) located at the southern tip of Africa being considered a global mega-diversity (Samways et al., 2024; Swart et al., 2015). This mega-diversity has been driven by topographic, climatic, sea-level, and geological uplift, without being exposed to major events such as glaciations since the breakup of Gondwana (Samways et al., 2024). Close to this is MNP, a world heritage site that is characterized by granite kopjes, collections of granite boulders, and cliffs surrounded by wooded valleys and grasslands forming unique habitats and climates (Barry et al., 2015). These habitats have been noted to host unique species, including birds. However, no study in the park has assessed the distribution of Diptera species, except samples deposited in the Natural History Museum of Zimbabwe (NHMZ) by David Hancock, yet such habitats are homes to the unsung heroes "dipteran fauna" that buzz, scavenge, decompose, and pollinate ecosystems, along other pollinators like bees.

As far as we could ascertain, no study has been conducted on the distribution and diversity of MNP across habitats and seasons, yet such studies are important to document the relative abundance, richness, and Shannon diversity of AD species across seasons and habitats before some species go extinct.

Seasonality is a conspicuous feature in the life history of many organisms, including Diptera, yet little is known about Diptera community composition shifts across habitats in MNP. Knowledge regarding the seasonal abundance of Diptera is therefore necessary for understanding the seasonal dynamics of these species. Recording and comparing the different species occurring in an area and over different seasons can provide valuable information on their responses to prevailing environmental and climatic conditions. For instance, species of carrion-associated flies differ spatially and temporally, due to variable factors such as food availability (Kirk-spriggs, 2007), suitable habitat, the presence or absence of other species, human disturbance (Akbarzadeh et al., 2015), climate, altitude, and season (Williams et al., 2009). Most of the research that has looked at seasonal fluctuations of Diptera species abundance indicates that more Diptera species are abundant during warm seasons compared to colder seasons. Notable variation between species tended to be more prevalent during colder seasons (Brundage et al., 2011). This seasonal variation has been attributed to intense competition for breeding resources between species utilizing an ephemeral resource such as carrion (Hanski, 1987). These seasonal sampling also serve as inventories in understudied ecosystems like MNP.

This study was conducted to determine the shifts in Diptera communities across seasons and habitats in MNP, a world heritage site which has much significance to history, culture and biodiversity in southern Africa. The objectives addressed in this research are (i) to assess the species composition and community structure of the AD, (ii) to determine the distribution of AD across habitats, and (iii) to determine the impacts of seasonality on AD in MNP. By sampling across habitats and seasons, this work also intended to serve as an inventory of the Diptera species in this under-studied area. Such inventories will be critical in setting up further research and monitoring programs for the Diptera species, which is an important aspect in decision making matrices in conservation.

4.3 Methods

4.3.1 Study area

The study was conducted in a world heritage site, MNP, Zimbabwe (20° 33' 26" S, 28° 30' 45" E, with altitudes ranging from 1200 – 1538 m). The 424 km² park was established in 1926 and declared a world heritage site in 2003. It is located in the south-western Zimbabwe. MNP is characterized by woodlands, grasslands, savanna woodland, and outcropping granite kopjes that create unique microclimates and habitats for insects, particularly diptera species. The kopjes in MNP occupy between 40 to 50% of the park's area (Barry et al., 2015). The park is dominated by loamy soils, savanna grasses (i.e., *Hyparrhenia* spp. and *H. contortus*), and the dominant tree genera include: *Vauchelia, Terminalia, Brachystegia, Kirkia, Commiphora, Euphorbia, Strychnos*, *Ficus*, and *Combretum* (Barry et al., 2015; Mlilo et al., 2015). The park has an average annual rainfall of 580 mm, received mostly between November and April, but occasional light rainfall activity can be experienced up to August (Mlilo et al., 2015).

The kopjes in MNP create a variety of habitats that are favorable for different wildlife species. The habitats such as woodlands, mountains, plains, rivers, and dams in MNP accommodate wildlife species such as the black rhino (*D. bicornis*), impalas (*A. melampus*), kudus (*T. strepsiceros*), giraffes (*G. camelopardalis*), waterbucks (*K. ellipsiprymnus*), leopards (*P. pardus*), monkeys (*C. pygerythrus*), baboons (*Papio* spp.), and wildebeests (*Connochaetes*), in which the wildebeest is the most dominant (Mlilo et al., 2015). ww

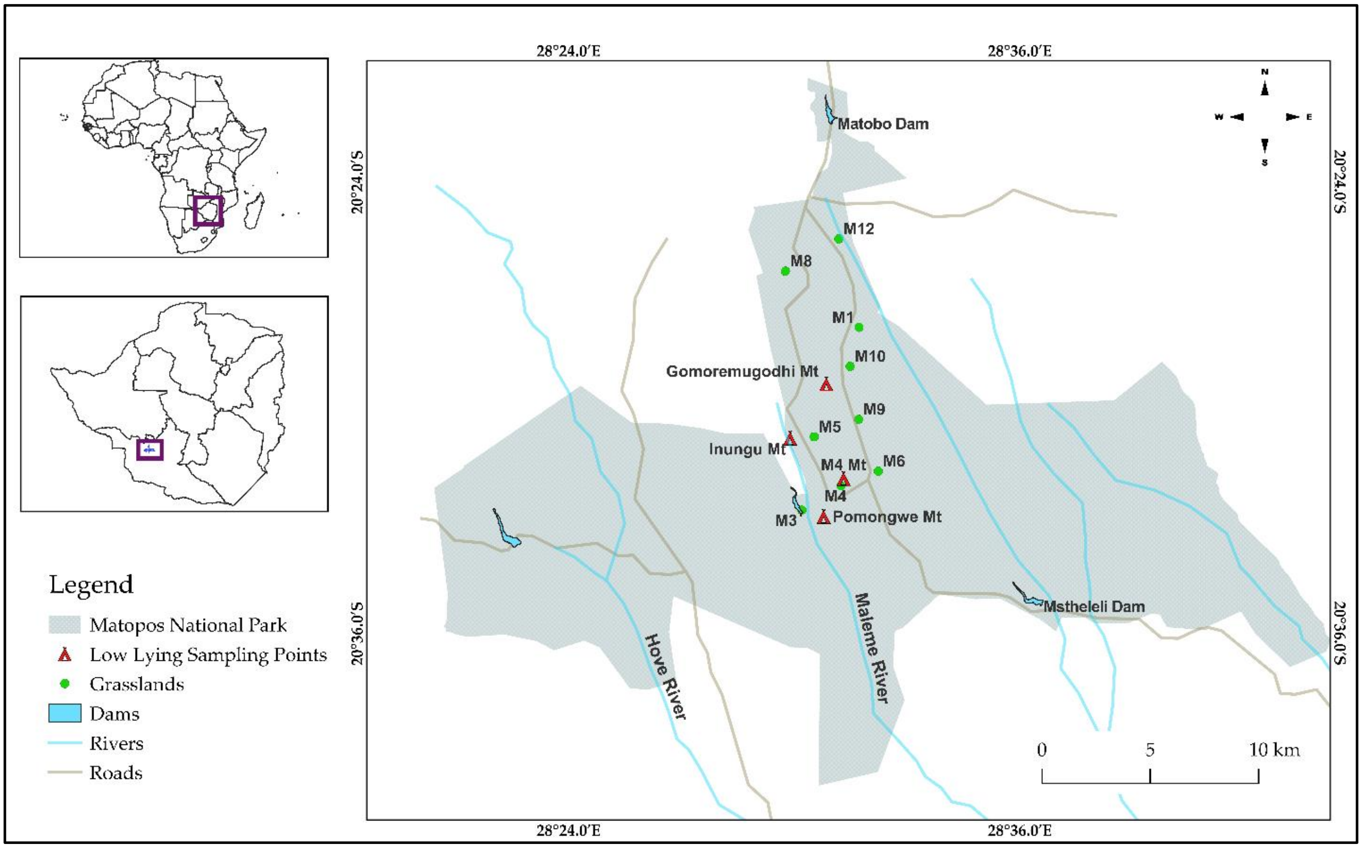

Fig. 4.2: Map of MNP with sampling sites across the park. Key: **MNP** = Matopos National Park. The **M** in sampling sites (M1, M2, M3, M4, M5, M6, M8, M9, M10, M11, M11, M12) = Matopos, **Mt** = Mountain. The habitat description of each site is given in Table 4.1.

4.4 Collection of AD specimens

Over a four-year period (between December 2021 and April 2025, except the year 2023 when there were logistical constraints), Diptera species were seasonally sampled. The seasons that were considered for this study were: Hot-dry (August - October), Hot-wet (November to March) and Cool-dry (May to July) seasons by using the pan trapping method (Kirks, 1984; West et al., 2008) across three main habitats (i.e., Mountains, Grasslands, and Woodlands). The GL and Mt habitats had 12 sampling sets (2 sets of each color) to ensure adequate representation. For mountains, sampling was conducted at three levels: foot, intermediate, and top of the mountains, using 1 set of pan traps (1 of each color) at each level. Site M7 was omitted from the sampling points due to inaccessibility as detailed in Table 4.1. Since Diptera species show differential colour preferences for pan traps, a range of pan trap colours: yellow, white, and blue were used. The colours that were used had low reflectance in the UV range (wavelength < 400 mm) (Brown, 2021). However, this was unlikely to affect the results of a comparative study of this nature, given that UV is another primary colour in bi-, tri-, and tetra-chromatic vision, and is no more or less important than any other primary colour. Then at each sampling site, a total of six pan traps were deployed (i.e., two of each colour (yellow, blue, and white)). The selection of points at each site was systematic: from the center of the site (marked on a GPS unit), then pan traps were laid after 5 m, 10 m, and 15 m in two opposite directions. The pan trap colour placement patterns were random, while ensuring that each side of the central point had one pan trap of each colour.

Each pan trap was filled with approximately 400 ml of soapy water and left for 24 hours. Each sampling session lasted one week (7 days). Diptera specimens were collected from the pan traps every 24 hours. After each collection, the pan traps were refilled and reset for the next 24-hour cycle, which continued for the full 7-day duration. All AD specimens captured in the pan traps were temporarily collected in vials, then pinned and stored in insect collecting boxes. Furthermore, the collected specimens were pinned and labeled according to date, sampling point, habitat type, and pan trap type, until subsequent determination at the species level, as illustrated in Table 4.1.

Table 4.1: List of sampling points in Matopos National Park, Zimbabwe.

Habitat Type	**Sample ID**	**Latitude**	**Longitude**
Grasslands	M1	28.54787	-20.0282
	M2	28.54761	-20.029
	M4	28.54583	-20.026
	M9	28.56393	-19.9447
	M10	28.55964	-19.9398
	M11	28.56605	-19.9378
Woodlands	M3	28.59502	-19.9491
	M5	28.53707	-19.9539
	M6	28.56675	-20.0211
	M8	28.52602	-19.9216
	M12	28.53145	-19.9334
Mountains	M4 Mt (levels: i, ii, iii)	28.52179	-20.5313
	Pomongwe (levels: i, ii, iii)	28.51248	-20.5481
	Gomoremugodhi (levels: i, ii, iii)	28.51119	-20.4864
	Inungu (levels: i, ii, iii)	28.49491	-20.5142

GL = Grasslands; **WL** = Woodlands, **M4 Mt** = M4 Mountain, **Mt** = Mountains.

4.5 Diptera identification

The collected morpho-species were morphologically identified by renouned entomologists based at the National Sugar Institute Laboratory in Morogoro, Tanzania, using standard identification keys. Most of the morpho-species were identified to genus level due to the unavailability of keys and the failure to dissect samples because they were dry.

4.6 Statistical analysis

To assess whether the sampling effort was sufficient, rarefaction of genus accumulation curves across sampling sessions was generated using "specaccum" from the *vegan* package in R (Oksanen et al., 2025).

For each habitat, season and year, the response variables (i.e., species abundance, richness, and Shannon diversity) were calculated using the Shannon-Wiener index. Normality of species abundance, richness, and Shannon diversity was tested using the Shapiro-Wilk test. The Shannon diversity was log transformed to meet normality assumptions but Species abundance and richness failed to meet the normality assumptions even after transformation attempts.

Due to the tendency of the response variables to be spatially auto-correlated, the Moran's I statistic was employed to determine spatial autocorrelation in species richness. The spatial weights matrix was derived from neighbor relationships among sampling points using the "sf" and "spdep" packages in R (Pebesma & Bivand, 2023). After determining that there was no evidence of spatial auto-correlation, Generalized Linear Models (GLMS) were performed to assess the relationship of habitat and season on Diptera diversity, abundance, and richness. The Poisson family was utilized for species abundance, a negative binomial for richness, and a *Gaussian* for the Shannon diversity. Model selection was performed using the *dredge* function from the *MuMIn* package to select the best fit model with the lowest Akaike Information Criterion (AIC).

To determine the probability of Diptera presence or absence in a habitat or season, binary variables for each Diptera family of interest were created. For each selected family, a new column was added to the dataset with a value of "0" indicating absence and "1" indicating presence. Diptera families with low observations, less than 10% occurrence across the study period (i.e., Agromyzidae, Apioceridae, Bibionidae, Chironomidae, Culicidae, Curtonotidae, Diopsidae, Pipunculidae, Dolichopodidae, Empididae, Ephydridae, Micropezidae, Nemestrinidae, Sciaridae, Stratiomyidae, Tephritidae, and Therevidae) were removed from the binomial regression models because there would not be much variation in the probability of being present or absent in a habitat or a season. Community composition of Diptera families was visualized using a non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarity among habitats and seasons. The fit of the NMDS analysis was confirmed with the stress measure, in which a value of < 0.174 generally indicates a fair fit. All analyses were conducted in R Version R.5.0 (R Core Team 2025).

4.7 Results

4.7.1 Sampling effort

From December 2021 to April 2025, seven sampling sessions were done across three main seasons (i.e., Hot-wet, Cool-dry, and Hot-dry), covering three habitat types (Mountains, Grasslands, and Woodlands). The rarefaction analysis across sessions showed continuous species accumulation and that in each habitat, there was still the possibility of encountering a new genus or species if sampling had continued (Fig. 4.3).

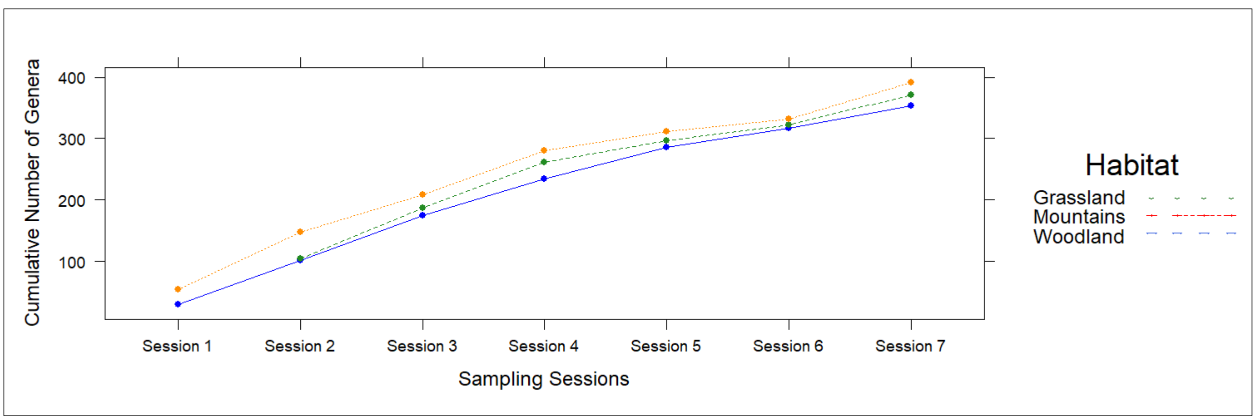

Fig. 4.3: Rarefaction of species accumulation across sampling sessions (session 1 – 7) in MNP between December 2021 and April 2025. A sampling session refers to a visit which was done in each season.

4.8 Distribution of the sampled individuals

Over four years and across three seasons, a total of 1,838 specimens were collected, representing 29 families and 94 genera (Appendix 2). Of the specimens collected, 58 species were identified

(Appendix 1) and the rest could only be identified to genus level. Of the specimens collected 39.8% of them were collected from grasslands, 32.3% from woodlands, and 27.9% from mountains. Also, of the specimens collected, 47.6% of the individuals were collected in the hot-wet, 36.3% in the hot-dry, and 16.1% in the cold-dry seasons. Regarding the identified 29 families, the most abundant families were Muscidae (24.15%), Lauxaniidae (14.25%), Rhiniidae (13.54%), Sarcophagidae (9.52%), Calliphoridae (8.48%), on the contrary the least collected were Tephritidae, Micropezidae, Dolichopodidae, Bibionidae, and Agromyzidae, each contributing 0.05%.

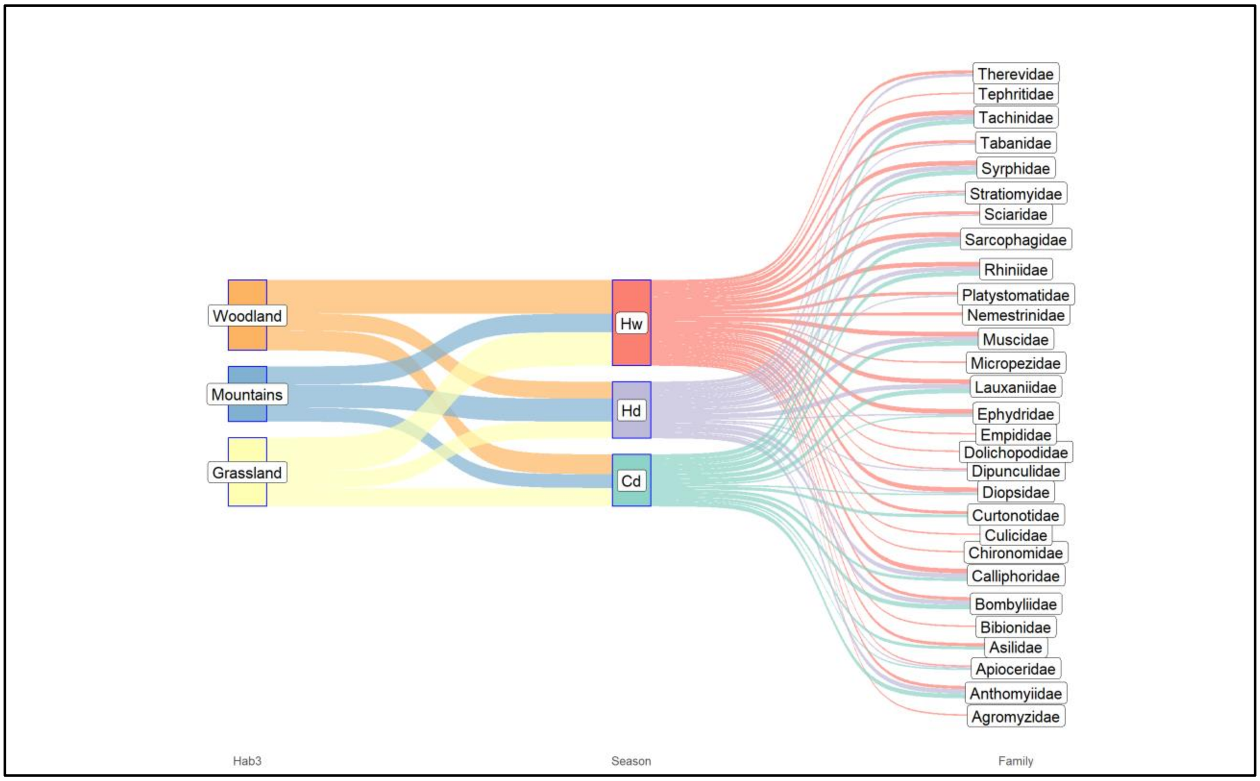

Fig. 4.4: Proportions of habitat type (to the left), seasons (in the middle), and Diptera families (to the right) recorded in MNP between December 2021 and April 2025. **Hw** = Hot-wet**, Hd** = Hot-dry**, Cd** = Cool-dry**.**

4.9 Species composition and Shannon diversity

Of the 94 genera collected, the most abundant genera were *Minettia* spp. (14.14%), *Anthomyia* spp. (7.18%), *Musca* spp. (7.12%), *Cosmina* spp. (6.74%), and *Dichaetomyia* spp. (6.42%), while the least collected genera included *Asarkina* spp. (0.05%), *Billaea* spp. (0.05%), and *Dilophus* spp. (0.05%), as illustrated in (Supplementary Table S2).

Regarding the relative abundance of the 20 genera during the study, the most abundant genus in hot-wet season was *Cosmina* sp, while the most abundant genus in the cool-dry and hot-dry was *Minettia* sp (Fig. 4.6). Similarly, the most abundant genera in grasslands were *Sarcophaga* sp and *Phumosia* sp, while *Cosmina* sp were the most abundant in mountains, while *Musca* sp, and *Minettia* sp were the most abundant in woodlands (Fig. 4.4). *Sarcophaga* sp and *Phumosia* sp were the most abundant in grasslands, *Dichaetomyia* sp, and *Anthomyia* sp, dominated the mountains. However, *Musca* sp dominated grasslands and woodlands, *Cosmina* sp dominated the grasslands and woodlands, whereas *Minettia* sp dominated the mountains and woodlands (Fig. 4.5).

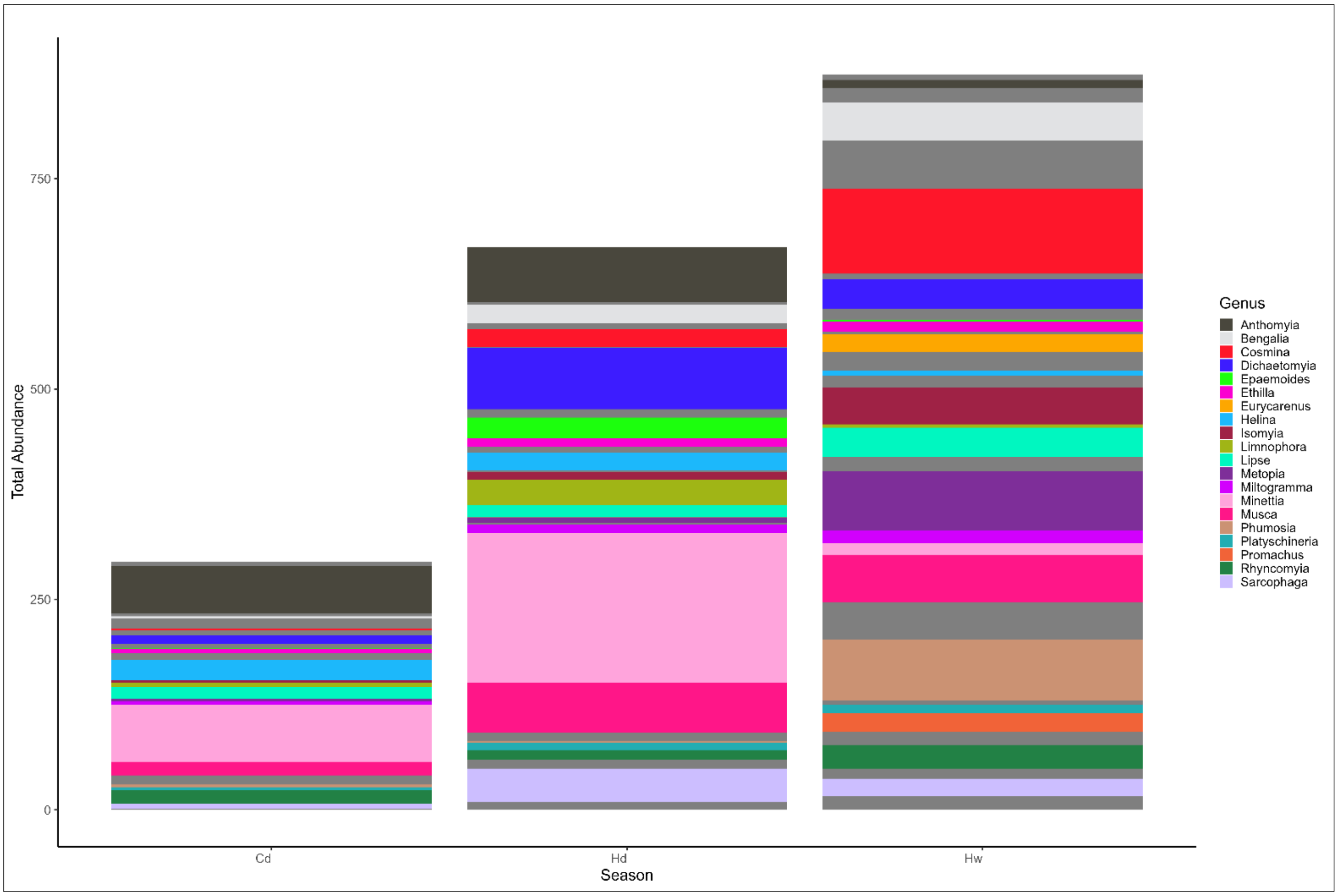

Fig. 4.5: The relative abundance of Diptera genera found across seasons in MNP. Hd and Hw are more similar in relative abundance compared to Cd. **Cd** = Cool-dry, **Hd** = Hot-dry; **Hw** = Hot-wet.

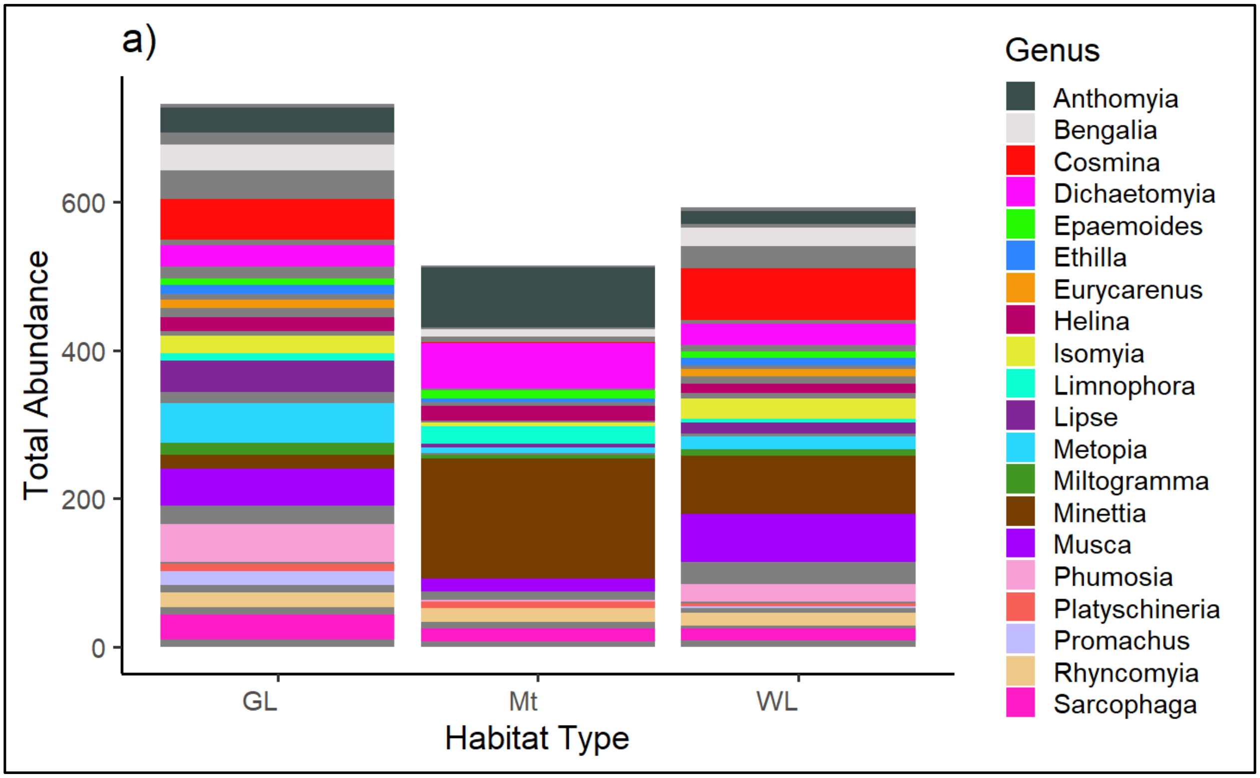

Fig.4.6: Relative abundances of Diptera species across habitats in MNP between December 2021 and April 2025. **GL** = Grasslands, **Mt** = Mountains; **WL** = Woodlands.

4.10 Relation between species abundance, richness, and Shannon diversity with habitat and season

The best GLM models retained habitat, season, and year as significant explanatory variables on species abundance, richness, and Shannon diversity. The highest species richness was significantly reported during the hot-wet season ($\beta = 17.0541$, SE = 0.7358, $p < 0.001$), but the lowest richness in the hot-dry season ($\beta = -6.789$, SE = 1.3584, $p = 0.0007$). Species diversity, on the contrary, peaked during the hot-dry seasons ($\beta = 1.11903$, SE = 0.02160, $p < 0.001$), but it significantly dropped during the cool-dry seasons ($\beta = 0.73124$, SE = 0.02975, $p < 0.001$). Species abundance, richness, and diversity were highest in grasslands, but species abundance, richness, and diversity were lowest in mountains, woodlands, and mountains, respectively, as illustrated in Table 4.2. These metrics also varied across the sampling years, with 2022 having the highest species abundance ($\beta = 0.6551$, SE = 0.08422, $p = 0.0471$), richness ($\beta = 11.8022$, SE = 0.6699, p <

0.0001), and diversity (β = 0.91607, SE = 0.02223, p < 0.001), howbeit species abundance (β = 0.23441, SE = 0.10168, p = 0.0127) and richness (β = -7.0117, SE = 0.7606, p < 0.001) being lowest in 2025 and species diversity being lowest in 2024 (β = 0.54676, SE = 0.03435, p < 0.001), as illustrated in Table 4.2 and Fig. 7a,b,c.

Table 4.2: Demonstrating the impacts of habitat type on species abundance, richness, and diversity in MNP between December 2021 and April 2025, except 2023.

Predictors	*β*	SE	Z/T-value	P-value
(a) Abundance			Z	
Intercept	0.48791	0.11048	4.416	< 0.001
Habitat-Mt	0.92577	0.06431	6.809	< 0.001
Habitat-WL	0.54854	0.05566	1.089	0.2760
Season-HD	0.26418	0.19142	-1.169	0.2425
Season-HW	0.4323	0.08301	-0.670	0.5029
Year 2022	0.6551	0.08422	1.985	0.0471
Year 2024	0.17733	0.16065	-1.933	0.0532
Year 2025	0.23441	0.10168	-2.493	0.0127
			T	
(**b) Species Richness**				
Intercept	-3.1190	0.9276	-3.363	0.00080
Habitat-Mt	-4.0928	0.5939	-1.640	0.101407
Habitat-WL	-4.9368	0.4579	-3.970	P < 0.001
Season-HD	-6.789	1.3584	-2.702	0.007026
Season-HW	17.0541	0.7358	27.417	P < 0.001
Year2022	11.8022	0.6699	22.274	P < 0.001
Year 2024	8.5135	1.2813	9.078	P < 0.001
Year 2025	-7.0117	0.7606	-5.118	P < 0.001
(c) Shannon Diversity			T	
Intercept	0.73124	0.02975	24.582	P < 0.001
Habitat-Mt	0.68281	0.01964	-2.465	0.01387
Habitat-WL	0.70182	0.01520	-1.935	0.05329
Season-HD	1.11903	0.02160	17.954	P < 0.001
Season-HW	1.10334	0.02309	16.118	P < 0.001
Year 2022	0.91607	0.02223	8.316	P < 0.001
Year 2024	0.54676	0.03435	-5.370	P < 0.001
Year 2025	0.66362	0.02520	-2.684	0.00741

Mt = Mountain, **WL** = Woodland, **HD** = Hot-dry, **HW** = Hot-wet.

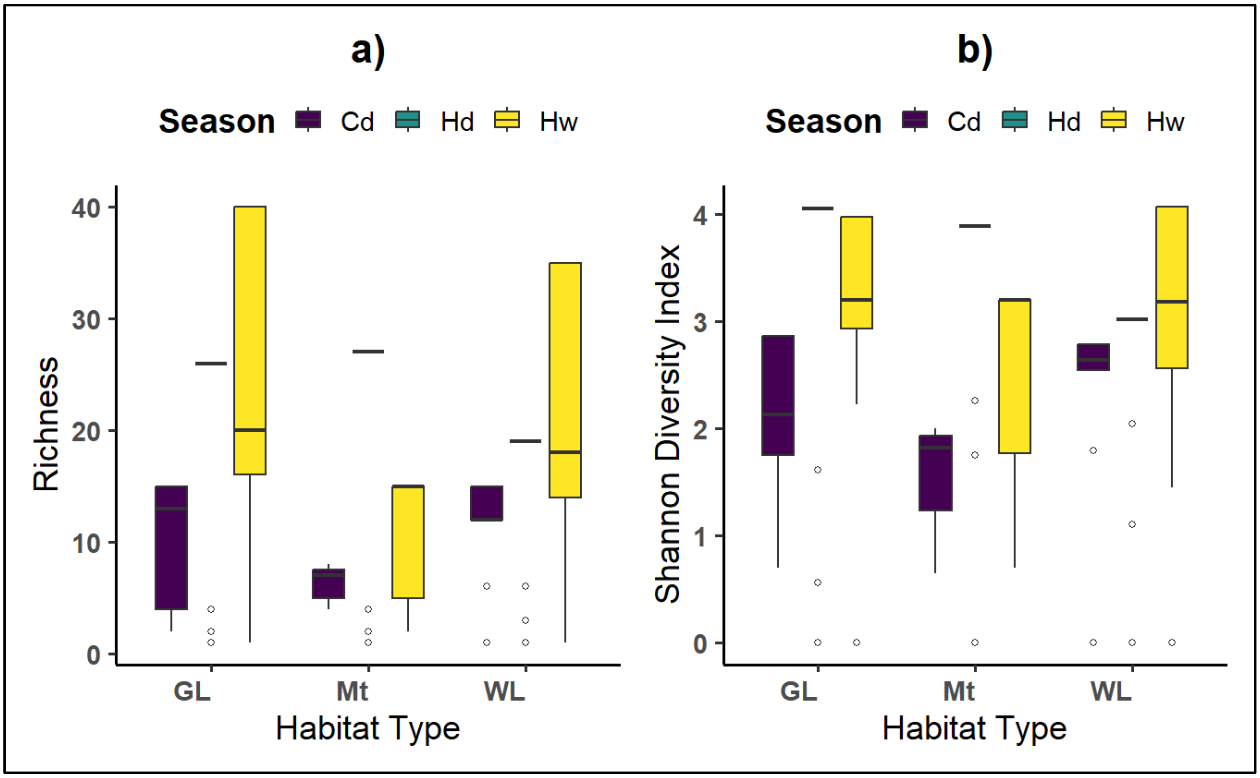

Fig. 4.7: (a) Species richness and (b) Shannon diversity index across habitats and seasons in MNP between December 2021 and April 2025. Habitats: **GL** = Grasslands, **Mt** = Mountains; **WL** = Woodlands. Season: **Cd** = Cool-dry, **Hd** = Hot-dry, **Hw** = Hot-wet.

4.11 The probability of AD families' occurrence by season, year, and habitat

Table 4.3: The probability of encountering Diptera families across habitats, seasons, and years

Family	Habitat influence	Season influence	Year influence
Anthomyiidae	Highest probability in mountains and least in grasslands.	Most likely recorded during the cool-dry season and least during the hot-wet season.	Not significant
Asilidae	Highest probability in woodlands, while the lowest in the mountains.	Highest probability in the hot-wet, but lowest in the hot-dry season.	Most of its records in the year 2024 and least in 2025.
Bombyliidae	Not significant	Not significant	Most of its records in the year 2024 and least in 2025.
Calliphoridae	Highest probability in woodlands, but lowest in grasslands.	Not significant	Most of its records in the year 2021 and least in 2024.
Muscidae	Not significant	Highest probability in hot-dry, but lowest in the hot-dry season.	Not significant
Lauxaniidae	Highest probability in mountains, but lowest in the woodlands.	Highest in the hot-dry season but lowest in the hot-wet.	Most of its records in the year 2024 and least in 2021.
Platystomatidae	Highest in woodlands, but lowest in mountains.	Highest in the cool-dry season, but lowest in hot-dry season.	Most of its records in the year 2021 and least in 2024.
Rhiniidae	Not significant	Highest probability in the hot-wet season, but lowest in the hot-dry season.	Most of its records in the year 2025 and least in 2021.
Tabanidae	Not significant	Highest chances of encountering the family being in hot-wet, but lowest in cool-dry season.	Most of its records in the year 2022 and least in 2025.

Tachinidae	Not significant	Not significant	Most of its records in the year 2022 and the least in 2021.

Location: Table 4.4, Fig. 4.8 and (Appendix 3a,b,c - 12a,b,c).

Table 4.4: The probability of encountering Diptera families occurring across seasons and habitats.

Response V.	Season				Habitat				Year				
Diptera Families	**Cd**	**Hd**	**Hd**	**Sig level**	**Mt**	**WL**	**GL**	**Sig level**	**2021**	**2022**	**2024**	**2025**	**Sig level**
Anthomyiidae	-2.5527	-3.3958	-4.7481	**0.0001**	-1.5715	-2.122	-2.5527	**0.001**	-2.5527	-2.63224	-1.75983	17.53576	
Asilidae	-4.09072	-20.0679	-1.96701	**0.0001**	-20.0591	-4.05525	-4.09072	**0.0001**	-4.09072	-4.35988	-2.59166	-6.82325	**0.0005**
Bombyliidae	-3.8027	-2.9206	-2.342		-3.9473	-3.3973	-3.8027		-3.8027	-4.3342	-2.6853	-4.9302	**0.002**
Calliphoridae	-2.0417	-2.2444	-1.9215		-2.5274	-1.9383	-2.0417	**0.040**	-2.0417	-2.3989	-18.3381	-2.6626	**0.006**
Muscidae	-0.46253	-0.53459	-1.37104	**0.0001**	-0.86232	-0.62772	-0.46253		-0.46253	-0.47279	-0.59171	-0.12145	
Lauxaniidae	-19.268	-17.7768	-19.5404	**0.0001**	-17.9523	-19.3448	-19.268	**0.0001**	-19.268	-4.14403	-2.5299	-3.18462	**0.0001**
Platystomatidae	-1.1514	15.6498	-1.9655	**0.006**	-17.7176	-0.9283	-1.1514	**0.015**	-1.1514	-21.8357	-37.6558	-21.4976	**0.0001**
Rhiniidae	-2.9222	-3.21352	-2.82662	**0.021**	-3.44342	-3.01716	-2.9222		-2.9222	-1.76148	-2.20496	-0.8045	**0.0001**
Sarcophagidae	-2.10239	-1.89098	-1.7931		-2.33075	-2.39282	-2.10239		-2.10239	-2.13555	-2.28348	-2.38959	
Syrphidae	-3.6318	-3.8775	-3.5225		-3.8899	-3.4109	-3.6318		-3.6318	-3.1077	-2.8937	-4.4118	

Tabanidae	-39.4917	0.995	0.994	**0.057**	0.541	0.491	-39.4917		-39.4917	0.994	0.999	1	**0.023**
Tachinidae	-3.73776	-3.9451	-3.74207		-4.03492	-3.72491	-3.73776		-3.73776	-2.23521	-2.36527	-2.33899	**0.035**

Cd = Cool-dry, **Hd** = Hot-dry, **Hw** = Hot-wet, **Mt** = Mountain, **WL** = Woodland, **GL** = Grassland, **Sig level** = Significance level.

Non-metric multidimensional scaling (NMDS) ordination (stress = 0.163) revealed clear seasonal structuring of Diptera communities, with partial overlap among habitats. The Hw season clustered to the right of the ordination and was associated with Asilidae, Platystomatidae, Tabanidae, Calliphoridae, and Rhiniidae. The Hd season occupied the central ordination space, overlapping with other seasons, and was linked to Tachinidae, Bombyliidae, and Muscidae. The Cd season was positioned to the left and was associated primarily with Anthomyiidae and Lauxaniidae. Habitat type showed weaker separation than season, although WL samples tended to align with Hw assemblages, Mt samples with Cd, and GL samples were widely distributed, as shown in Fig. 4.8.

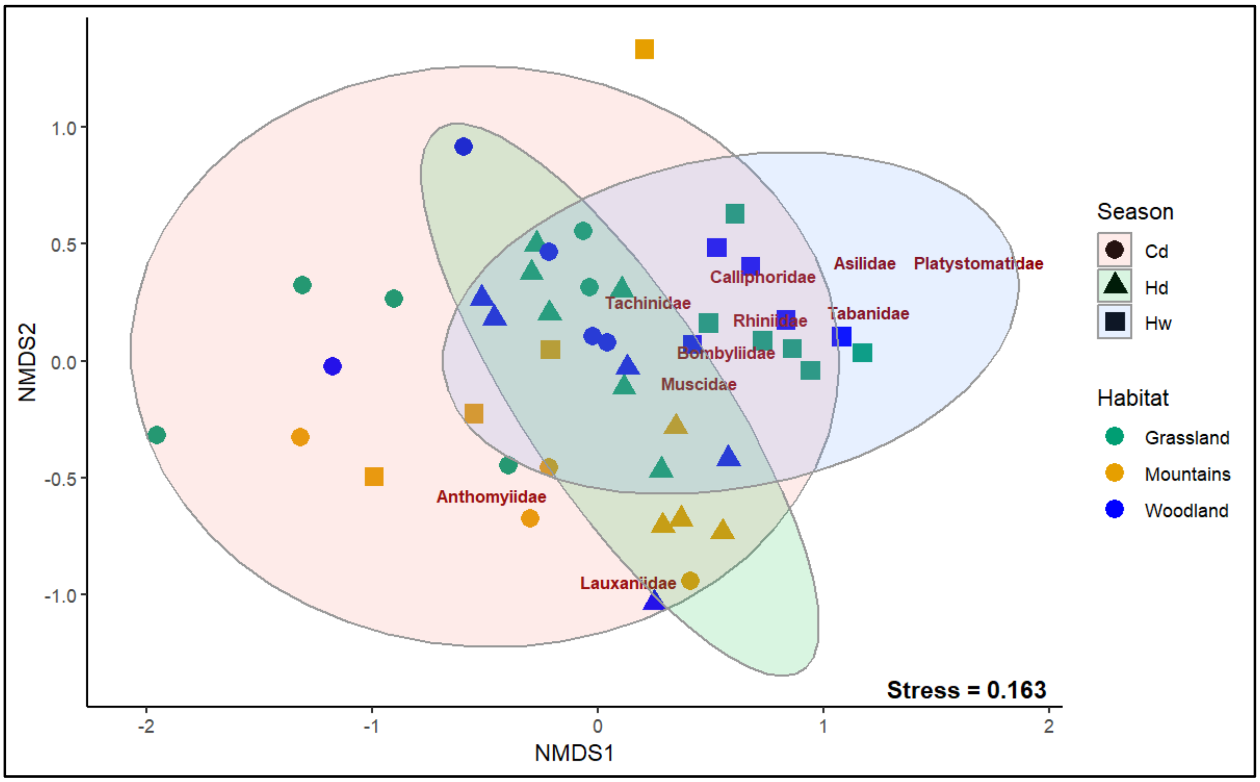

Fig. 4.8: Non-metric multidimensional scaling (NMDS) of habitat type across season and habitat in MNP between December 2021 and April 2025, except 2024. (Stress = 0.163). Cd = Cool-dry, Hd = Hot-dry, Hw = Hot-wet seasons.

4.12 Discussion

The most abundant genera were *Minettia* sp, *Anthomyia* sp, *Cosmina* sp, *Musca* sp, and *Dichaetomyia* sp, but the least dominant genera included *Asarkina* sp *and Billaea* sp. The highest abundance of *Minettia* sp, *Anthomyia* sp, and *Cosmina* sp might have been correlated with mountains and woodland habitats. The abundance of *Musca* sp was expected as the park has a high number of mammalian presence (both wildlife and livestock) and the open grasslands (Parry et al., 2016). Dung and carrion from these animals could have attracted more *Dichaetomyia* sp and influenced a strong scavenger network (Banerjee & Hore, 2017). The most observed genera may suggest a strong functioning decomposition system, and probably the most diverse habitats (from shady to open habitats) that accommodate an array of the dipteran fauna (Adler & Courtney, 2019). However, the least abundance of *Asarkina* sp and *Billaea* sp may reflect specialist niches The limited collection of Tephritidae in this study is likely due to the method used (pan trapping), which tends to attract visually-oriented Diptera species rather than those with reduced visual capabilities. Therefore, employing multiple sampling techniques, such as malaise trapping, sweep netting, and light traps, would provide a more comprehensive representation of Diptera species.

Species abundance, richness, and diversity varied across habitats in MNP, with grasslands having the highest species abundance, richness, and diversity, while species abundance and richness were lowest in woodlands, and species diversity was lowest in mountain habitats. This is consistent with the results of Mulieri et al. (2022), who recorded 15 species of Sarcophagidae in grasslands compared to 7 species collected in forests. Similarly, Cazorla & Campos (2020) observed high species diversity in grasslands but high dominance in forests. Such discrepancies exist especially when targeting specific groups of Diptera species. For instance, a study by Montoya et al. (2021) in northwestern Colombia Paramos observed otherwise. They discovered the reverse of this study's findings, with a Paramo (high mountain systems located >3,000 m of altitude) having the highest richness and number of collected specimens, followed by forest, and grassland. Generally, high species abundance, richness, and diversity observed during the study might relate to the use of pan traps that were more easily seen in grasslands than in other habitat types. However, floral diversity and microhabitats and carrion as well as dung in grasslands from wildlife species and livestock could have also contributed to this diversity. Furthermore, mountains in Matopos are not easily accessible by cattle and the majority of mammalian herbivores. This could have contributed to low Diptera abundance, richness, and diversity in mountains as compared to grasslands and woodlands.

However, low species abundance, richness, and diversity observed in woodlands might be attributed to the fact that most trees offer concentrates in the canopy, thereby limiting the number of individuals collected in the undergrowth.

This study reported the seasonal variation of the composition and diversity of Diptera species in Matopos National Park, with the highest species richness reported during the hot-wet season and the lowest richness in the hot-dry season. Species diversity, on the contrary, peaked during the hot-dry seasons but dropped during the cool-dry seasons. These results were expected, as hot-wet seasons are commonly associated with optimal conditions for Diptera species, with abundant resources (e.g., water, floristic diversity) supporting higher species richness and diversity. Moreover, Diptera species might have adapted to survive in the hot-dry season, maintaining stable abundance despite harsh conditions. Interestingly, temperature, humidity, and vegetation structure might have influenced species diversity, with the hot-dry season favoring certain species. Wiegmann et al. (2011) confirmed these findings when they noted higher Diptera abundances in summer than those in winter. But, since different species adapt differently to weather elements (as some will be avoiding competition), continued sampling is needed to assess trends of species that dominate the cool-dry seasons.

These metrics (i.e., species abundance, richness, and diversity) also varied across the sampling years, with 2022 having the highest species abundance, richness, and diversity, but 2025 and 2024 having the lowest abundance and richness respectively. These variations could have influenced variations of species abundance, richness, and diversity over the sampling period.

The logistic regression models revealed that the odds of encountering Anthomyiidae, Muscidae, and Platystomatidae were high during the cool-dry season compared to other seasons, whereas the likelihood of encountering Asilidae, Rhiniidae, and Tabanidae was high in hot-wet. However, the odds of encountering the family Lauxaniidae were high during the hot-dry season. Furthermore, Asilidae, Bombyliidae, and Lauxaniidae were highly encountered in 2024, while Calliphoridae, Platystomatidae were encountered in 2021, Rhiniidae in 2025, and Tabanidae, Tachinidae in 2022. Moreover, the odds of encountering Asilidae, Calliphoridae, and Platystomatidae were high in woodlands compared to other habitats. The likelihood of encountering Anthomyiidae and Lauxaniidae in mountains. However, the odds of encountering Muscidae, Sarcophagidae, Syrphidae, and Tachinidae not vary by habitat, neither did the odds of encountering Sarcophagidae, Syrphidae, and Tachinidae vary by season or by year for Muscidae, Sarcophagidae, and Syrphidae. These findings suggest a complex interplay between climate and habitat that warrants further investigation into the ecological needs of these Diptera families

(Naskar et al., 2019). However, it is also essential to consider that some families, like Muscidae and Sarcophagidae, did not show significant variation across seasons or habitats, indicating potential resilience or adaptability to environmental changes (Paul et al., 2024).

4.13 Conclusion

This study revealed significant variations in species abundance, richness, and diversity. Major findings included habitat-specific patterns, in which different habitats (e.g., grasslands, woodlands, mountains) supported unique Diptera assemblages, with grasslands exhibiting the highest species richness and diversity. On the contrary, seasonal fluctuations significantly contributed to the variation of Diptera species, with some families like Muscidae and Lauxaniidae more abundant during hot-dry season. Furthermore, Diptera populations fluctuate across years, with 2022 showing the highest species abundance, richness, and diversity. Lastly, different Diptera families responded differently to habitat and seasonal changes, highlighting the importance of considering these factors in conservation efforts. This study is relatively new in this park, and indeed it will serve as a basis on which other scientists can build. It also helped in the understanding of Diptera communities in MNP, while providing valuable insights for conservation strategies and ecological monitoring.

4.14 Chapter summary

Results from this work demonstrated that seasonality and habitat type significantly influenced the distribution, composition, and community structure of Diptera species in MNP, Zimbabwe, with grasslands hosting the highest species abundance, richness, and diversity, but species abundance, richness, and diversity were lowest in mountains, woodlands, and mountains, respectively. Further, the highest species richness was reported during the hot-wet season, but the lowest richness in the hot-dry season. Species diversity, on the contrary, peaked during the hot-dry seasons, but it significantly dropped during the cool-dry seasons.

Chapter 5

Design and implementation of a mobile application for Afrotropical Diptera identification using a Google Teachable Machine

5.1 Context

This chapter demonstrates how the training of machine learning (ML) model was done on Google Teachable Machine. The chapter illustrates how the mobile application was evaluated (its ability to identify Diptera specimens as per training, and measures the time taken to identify the specimens). Knowing that mobile applications misbehave at times, this study assessed how the application performed when given pictures from different backgrounds. The conceptual framework below demonstrates the areas considered when designing the application (Fig. 5.1.)

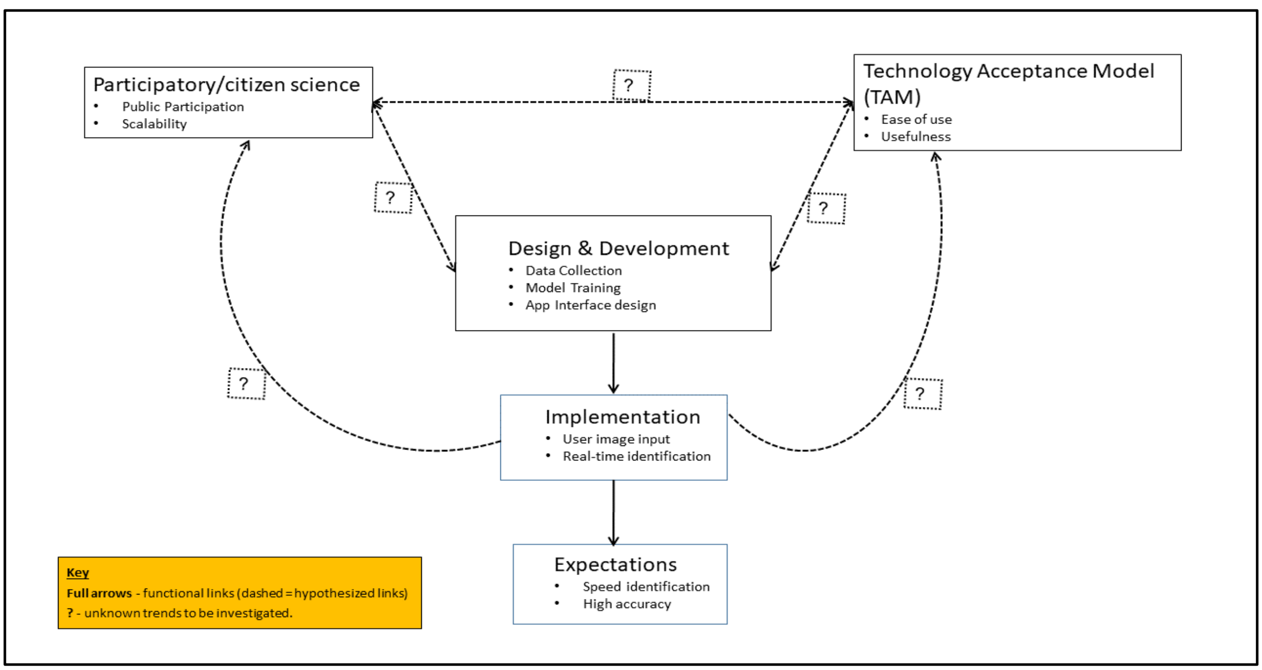

Fig. 5.1: The conceptual framework used Design and implementation of a mobile application for AD identification using a Google Teachable Machine.[3]

5.2 Abstract

Taxonomic impediments coupled with a lack of Diptera taxonomic experts and collection curators from the Afrotropical Region (except for South Africa) have contributed to the understudied nature of the AD. Accurate species classification is the basis of all aspects of taxonomic research and is an important aspect of workflows in biological research. Fortunately, machine learning used in conjunction with mobile applications offers opportunities for automated species identification. Taxonomists can benefit from this by making identification easier. In this paper, Diptera species were morphologically identified at the Laboratory of the National Sugar Institute in Morogoro, Tanzania. Then, a dataset included 500 different images for each of the 30 Diptera genus/species was created. A supervised learning model for species identification was trained using a Google Teachable Machine and exported as a TensorFlow Lite, and then integrated it into a mobile application to identify 30 species. The mobile application, which was named FlySpotter rides on the functionalities of smartphones, takes photos of Diptera species, and performs image processing to provide information about its name, biology, and confidence levels. As it stands, the application can identify the 30 Diptera species in a mobile environment. Given more data, this technology has the potential to revolutionize Diptera identification alongside other advancements like DNA barcoding.

Keywords: Afrotropical Diptera identification, Google Teachable Machine, mobile application, taxonomy

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[3] This chapter is a manuscript in preparation for MethodX with the following details:

Matengo T, Tarakini G, Musundire R, Khumalo W, and Tarakini T (**in preparation**). Design and Implementation of a mobile application (FlySpotter) for Afrotropical diptera identification using a Google Teachable Machine.

The intellectual property registration is ongoing, having been scored 80% by the Innovation committee at Chinhoyi University of technology.

5.3 Introduction

It is widely acknowledged that a significant portion of the earth's animal diversity, estimated by zoologists, includes between three to five million species that remain undiscovered and understudied (Audisio, 2017; Zhang et al., 2009). Even the understanding of the less than two million living animal species that have been described is inadequate. This lack of knowledge is especially pronounced for invertebrates, as people have minimal information about their ecology, distribution, genetic makeup, life history, and conservation status. Ongoing human activities are causing worrying rates of habitat loss, fragmentation, and simplification, making this situation even more urgent (Babí Almenar et al., 2019; Ingram, 1996). Furthermore, the scientific and taxonomic communities are urgently called to address this significant taxonomic gap, often called the "Linnaean shortfall" or the taxonomic impediment (Audisio, 2017; Pollock, 2002). Diptera species are different, as sorting them relies mainly on the manual examination of morphological keys and taxonomic characteristics, which is challenging, especially for the minute, fragile, and similar species (Brown, 2021).

The taxonomy work, particularly for insects, is often constrained by limited time and funding (Doherty et al., 2023). For ages, morphological identification has remained the cornerstone of insect taxonomy (Gao et al., 2024). However, this method is not without its drawbacks. The complexity and time-consuming nature of morphological identification demand a high level of expertise and extensive experience, which can lead to misdiagnosis if not executed correctly (Doherty et al., 2023; Zhang et al., 2016). The traditional classification process is further hindered by several factors, including the uneven representation of morphological characters, the complexities involved in manipulating these representations, and the difficulties associated with accessing (Nkulu et al., 2023). These challenges create significant barriers for researchers, contributing to the understudied nature of many Diptera species globally. Hence, there is a dire need to come up with ways that will help to ease the identification process.

To address these limitations, technological advances in AI and GTM offer opportunities to train models to identify Diptera species from images with minimal coding skills (Afarini & Hindarto, 2024; Carney et al., 2020). These technologies have opened up new opportunities for research and applications in different fields, for instance, conservation biology and ecology (Afarini & Hindarto, 2024). GTM is based on TensorFlow, which is a Javascript library of ML algorithms. In light of these opportunities, GTM holds great promise in revolutionizing the field of entomology (Hartbauer, 2024; Kumar et al., 2020), alongside DNA barcoding (Meier et al., 2006; Ruiz-Arrondo et al., 2018). Machine learning, a field of artificial intelligence, assists computers to learn from data to perform tasks independently (Wong & Fadzly, 2022), helps to identify data patterns and make decisions about new datasets based on previous data. Previous studies have applied this technology in various fields and demonstrated the promising power of computer vision techniques in Diptera classification (Remboski et al., 2018). For instance, Silva et al. (2013) used audio analysis techniques and various ML algorithms to detect *A. aegypti*, *A. gambiae* Say, *C. quinquefasciatus* Say, and *C. tarsalis*, and achieved an accuracy rate ranging from 50.91% to 87.33%. Machine learning can enhance the identification process by automating the analysis of morphological data, thus reducing the reliance on expert judgment (Sapkota et al., 2020), which has been dwindling over the years in the Afrotropical region (Jordaens et al., 2024). Tools such as image recognition software can be trained on large datasets of insect images, allowing for rapid and accurate classification of species based on their distinctive morphological traits (Siria et al., 2022). If more financial resources, time, and data are channeled towards the training of strong models using machine learning and the development of mobile applications with user-friendly interfaces, Diptera identification can be made easier, and more citizen scientists can be encouraged to participate in Diptera conservation.

The development of localized mobile applications could facilitate broader participation in insect identification and taxonomy. By leveraging machine learning algorithms and user-friendly interfaces, these applications could empower amateur naturalists, researchers, and citizen scientists to contribute to data collection and species identification efforts (Goëau et al., 2013). This taxonomic research can lead to an increase in biodiversity records, particularly for understudied or endangered invertebrate species that may be on the brink of extinction before being properly described.

This study focused on (i) designing and implementing a mobile application that leverages machine learning to facilitate the identification of AD species of MNP.

5.4 Methods

5.4.1 Collection of AD specimens

In four years (December 2021 – April 2025, with the exception the year 2023), Diptera specimens were collected using pan traps across seasons: Hot dry, Hot-wet, and Cool-dry seasons and three main habitats (i.e., mountains, woodlands, and grasslands) in Matopos National Park (MNP), south west Zimbabwe.

5.4.2 Dataset creation

An AD dataset was created containing 15,000 images of the 30 AD species collected from MNP. To train the model, pictures were taken from various angles (i.e. dorsal, lateral, ventral, and frontal views) (Fig. 5.2). Then, approximately 500 images were taken of each sample genus/species of the 30 Diptera species as illustrated in Table 5.2. Each sample was placed on different backgrounds to train the model to cater for any variations in the natural environment. Images were taken using a Sony camera and a Dell laptop whose specifications are summarized in Table 5.1.

Table 5.1: The camera and Laptop specifications used in image gathering

Description	**Specifications**
Model Name	Sony α7RIII
Resolution	42 Megapixels
Image Sensor	35mm FULL-FRAME CMOS
Lens Model	FE 2.8/90 MACRO G OSS
Dell core i5	12th Gen, 21 GB RAM, 256 ROM

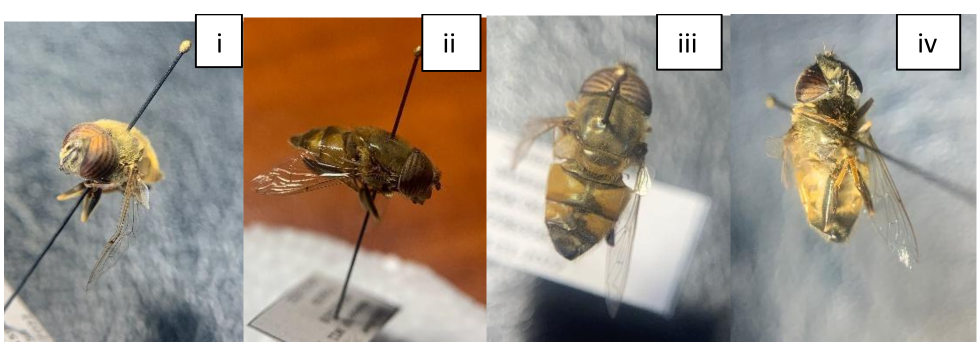

Fig. 5.2: Examples of different orientations; i) frontal, ii) lateral, iii) dorsal, and iv) ventral, in which the specimens were captured for training in the Google Teachable machine.

Table 5.2: List of Diptera Genus/Species that were tested using machine learning

No.	**Family**	**Genus/Species**
1	Asilidae	*Alcimus* sp
2		*Mesoleptogaster* sp
3	Bombyliidae	*Adelidea* sp
4		*B. discoidea*
5		*B. discolor*
6		*Eurycarenus* sp
7		*Palintonus* sp
8		*Systochus* sp
9	Calliphoridae	*P. westermanni*
10	Diopsidae	*Chaetodiopsis* sp
11	Platystomatidae	*B. caffra*
12		*Furcamyia* sp
13	Rhiniidae	*I. electa*
14		*I. facialis*
15	Sarcophadidae	*S. africa*
16	Sratiomyidae	*H. illucens*
17	Syrphidae	*A. amoena*
18		*E. taeniops*
19		*M. capensis*
20		*P. incisa*
21	Tabanidae	*Philoliche* sp
22		*A. rusticus*
23		*H. bigoti*
24		*Tabanus* sp
25	Tachinidae	*Chromatophania* sp
26		*D. bombylans*
27		*Ethilla* sp
28		*Exorista* sp
29		*Platyschineria* sp
30	Therevidae	*Xestomyza* sp

5.5 Model training

GTM 2.0 (https://teachablemachine.withgoogle.com/) was accessed through the researcher's Google account. Then, 15,000 images belonging to 30 Diptera specimens were uploaded to the GTM (since this was a supervised machine learning model). Then, each genus/species in GTM was trained with class images. The classified images were processed and analyzed using the "training" function in the ML, as illustrated in Fig. 5.3. Once the processing was completed, a name was allocated to the project, and the model was saved on cloud storage. Lastly, the model was exported as a TensorFlow Lite (TFLite) file and attached to a mobile application to identify other specimens as illustrated in Fig. 5.4.

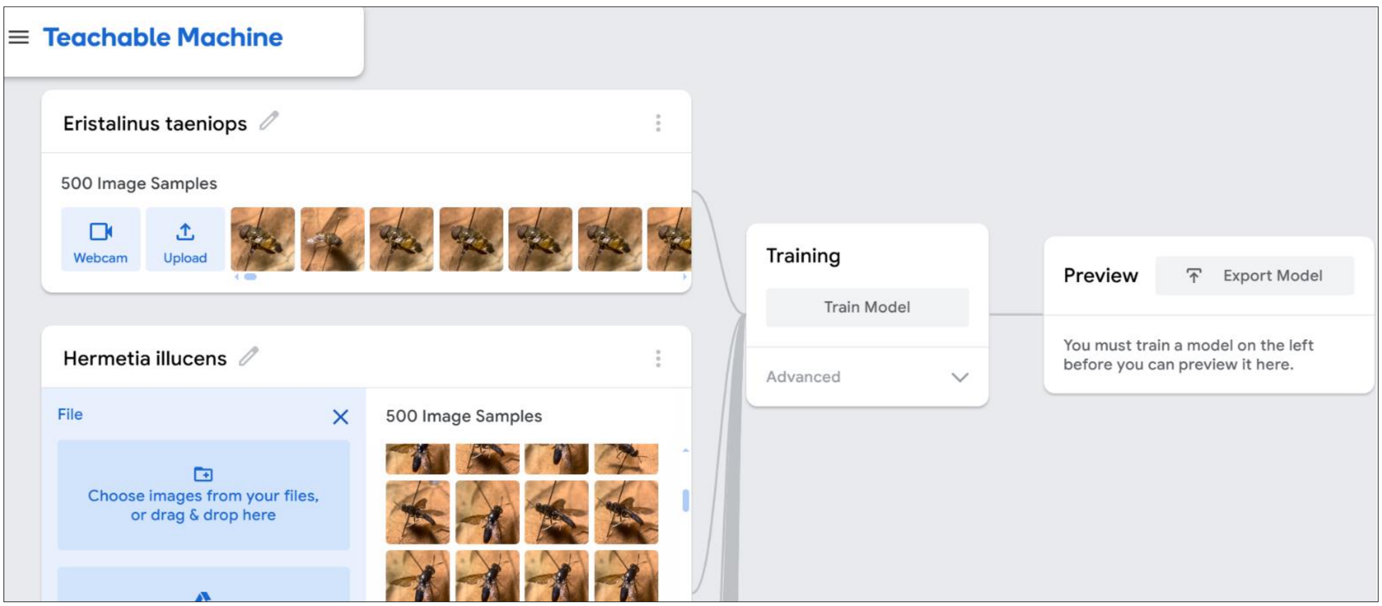

Fig. 5.3: Illustration of a Google Teachable Machine and the stages followed during the model training.

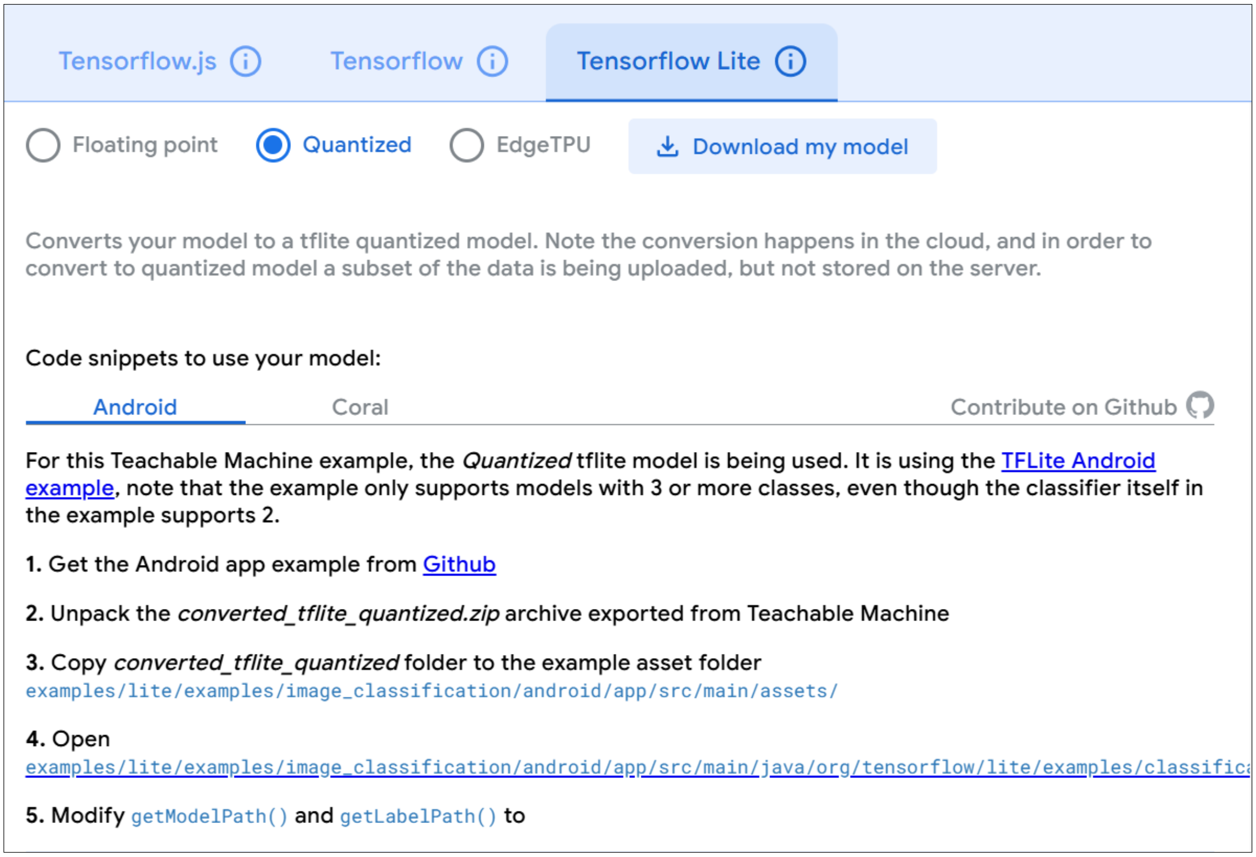

Fig. 5.4: The way in which the model was saved after training in GTM. **GTM** = Google Teachable Machine.

5.6 Android application

5.6.1 Acquiring the input image

Therefore, the android application (AA) was designed to interact with the model. Since the application relies on captured images, it requires the device to have a functional camera for it to be installed. The application provides two ways to acquire a Diptera image to be identified, firstly from a saved picture or one taken directly using the phone's camera. For the latter option, the specimen should be positioned to fit in the capture view provided in the application. Camera quality may differ across device models. Thus, prediction confidence may also differ from each device. When users select an image stored in their device as input to the classifier, the chosen image will undergo square ratio cropping as illustrated in Fig. 5.5. The application only identifies those species that it has been trained on, with everything else being classified as unknown. The mobile application was named FlySpotter. The application also provides information about the identified specimen and a fun fact (ecological function/ecosystem service) about the genus/species, as the application has been connected to AI to generate responses of the identified morpho-species.

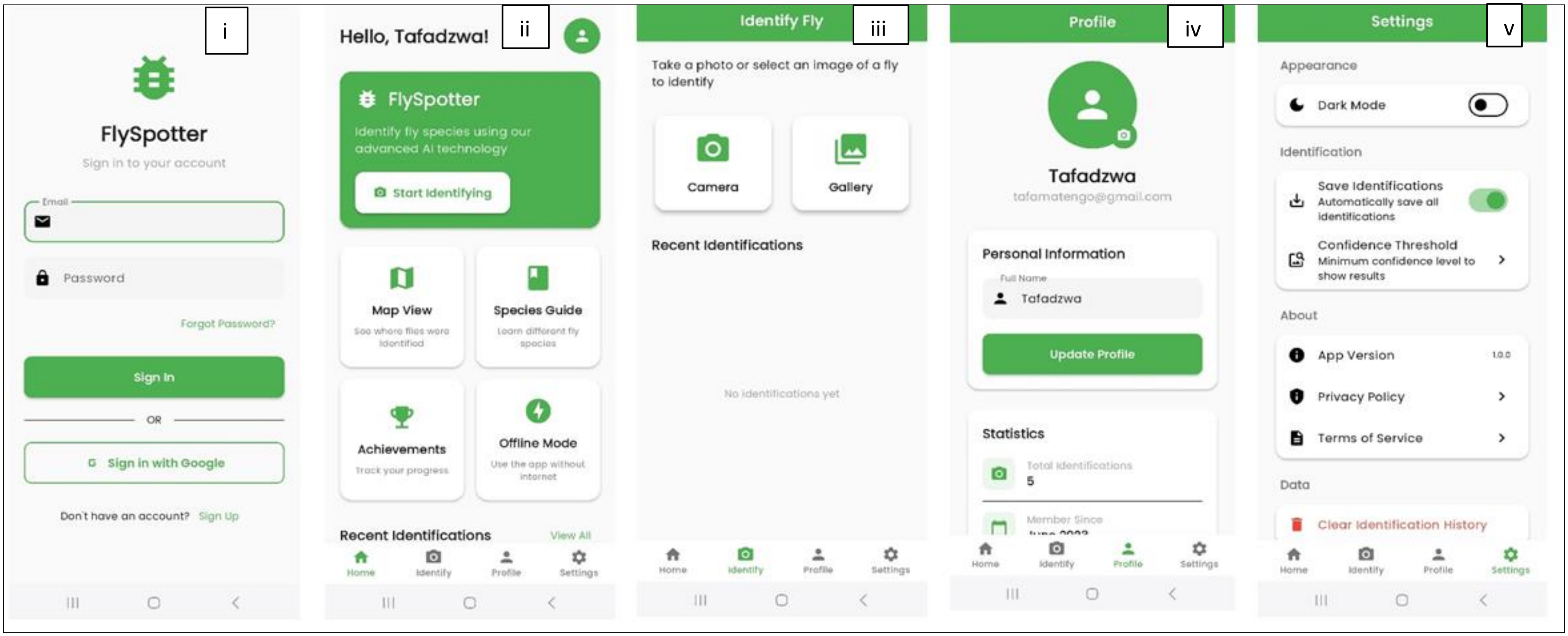

Fig. 5.52: An illustration of the: (i) sign-in page, (ii) home page, (iii) identifying page, (iv) Profile page, and (v) settings page of the mobile application developed at CUT. The **sign-in page** allows users to create an account and access the application, the **home page** has options like the Map view, Species guide, achievements, and the offline mode. The **identifying page** allows users to either directly take photos or use the ones in the gallery. The last two pages (**profile and settings**) allow users to see their personal information and their statistics of the identified species, while the **settings pages** allow users to save and change the mode (either dark or light mode) among other things.

5.7 Results

5.7.1 Confusion matrix

Of the 90 images used for testing, the application managed to predict every species with confidence levels that ranged from 71 – 100%, and higher scores were recorded when a sample used in the training was used as a test. The application, however, had difficulties in processing images of low-quality, although it managed to correctly identify the morpho-species, as illustrated in Figure 5.6.

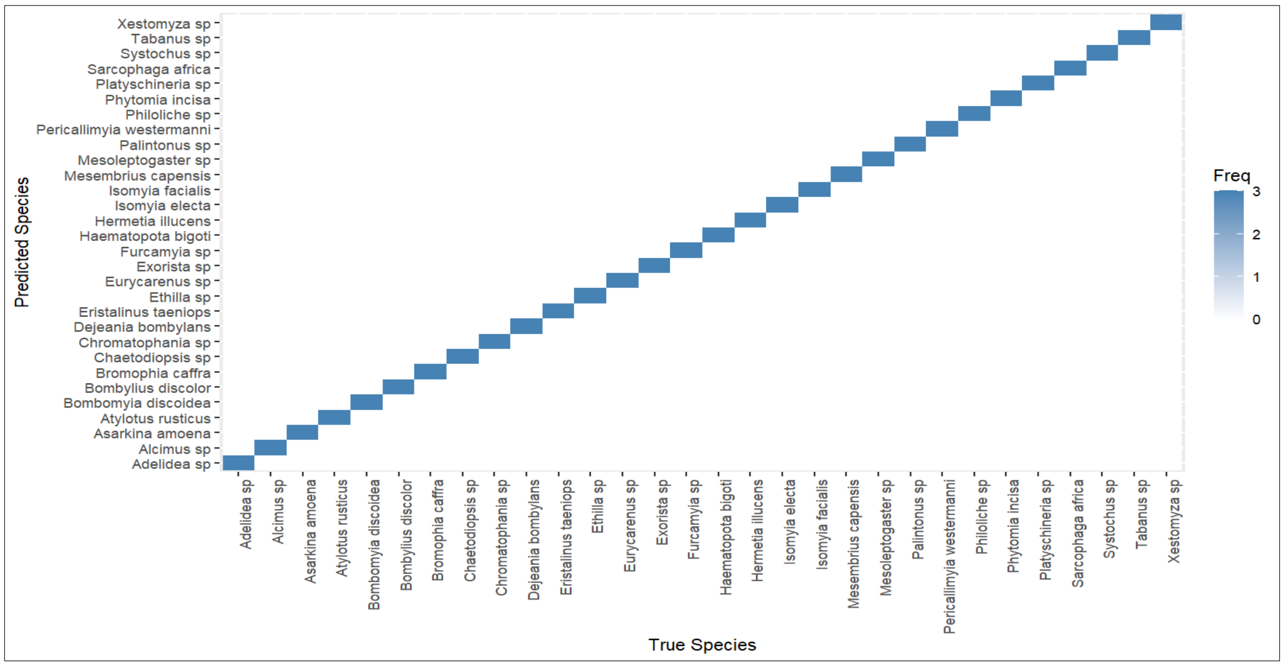

Fig. 5.6: Confusion Matrix of the predicted species.

5.8 Identification page

The users have two options when identifying species. First, take a photo of the specimen, click start identifying, or choose an image from the gallery, then click identify. The application takes ~5 seconds to identify a specimen on a good WiFi. The results are displayed in two forms: 1) an image with a name, and then an AI-generated text below detailing the species' general biology, importance, and a fun fact about the species, as illustrated in Fig. 5.7.

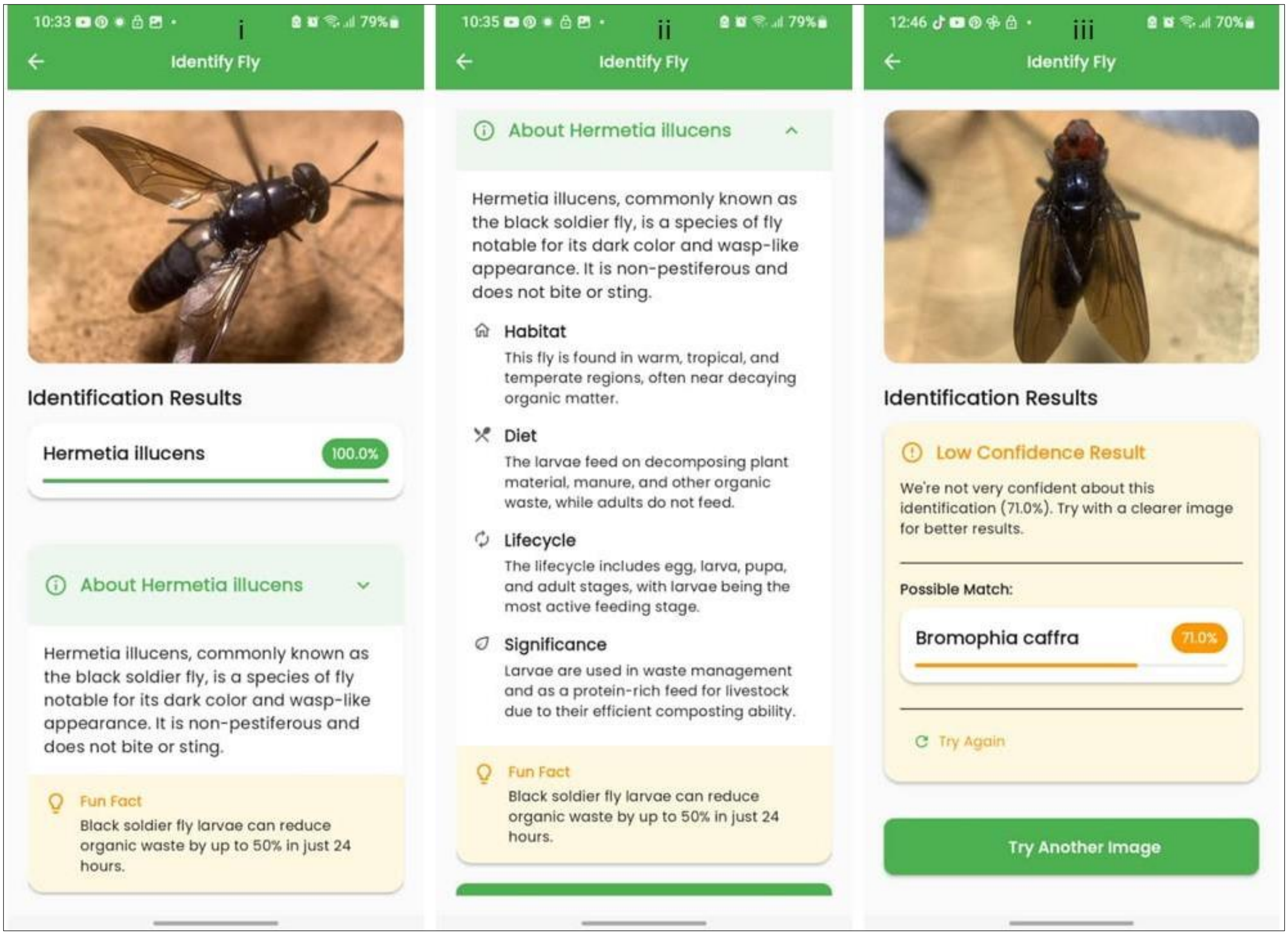

Fig. 5.7: The identification page illustrates: (i) species identification with confidence levels, (ii) about the species, and the recommendation the application gives when a low-quality image is used to identify species.

5.9 Discussion

FlySpotter's ability to provide real-time species identification aligns with the growing trend of using ML and AI in biodiversity research. For instance, the iNaturalist platform leverages AI to identify species from user-uploaded images, though it covers a broader range of taxa rather than focusing exclusively on Diptera. Similarly, the Pl@ntNet application specializes in plant species identification and has demonstrated the effectiveness of AI-driven tools in reducing the workload of researchers and amateurs (Joly et al., 2014). Applications like FlySpotter eliminates the need for manual reference to taxonomic keys, a feature shared by other AI-based identification tools. For example, the Merlin Bird ID application simplifies bird identification by analyzing user-submitted photos and audio recordings. Such tools have been shown to increase accessibility and engagement among non-experts (Sullivan et al., 2014).

The inclusion of ecological facts in FlySpotter's output enhances its educational potential. This feature is reminiscent of the Seek app by iNaturalist, which provides users with information about the species they encounter, fostering curiosity and learning (Pocock et al., 2017). However, lack FlySpotter's current inability to incorporate geotagging and geolocation limits its utility in narrowing down species ranges. Geospatial data is a critical component of biodiversity research, as demonstrated by platforms like GBIF (Global Biodiversity Information Facility), which rely on location data to map species distributions (GBIF, 2023). Integrating such features would make FlySpotter more aligned with modern biodiversity monitoring practices.

Although the FlySpotter's did not detect new species in this study, with additional data and training, it can potentially flag suspected new species for further investigation. This would streamline the identification process for known species, allowing taxonomists to focus on describing and discovering new ones. The iNaturalist is a perfect example, it allow users to contribute observations that can later be verified by experts, potentially leading to the discovery of new species (Ueda et al., 2018). Implementing a similar feature in FlySpotter, with a verification process involving specialists, would enhance its scientific value.

FlySpotter’s effectiveness depends on the comprehensiveness of its database. Studies have shown that machine learning models improve with increased data input (Wäldchen & Mäder, 2018). Expanding FlySpotter’s database to include more species and allowing users to contribute new data would improve its accuracy and utility. A citizen science platform like iNaturalist uses AI for species identification and allows users to contribute observations. It has been instrumental in documenting biodiversity and engaging the public (Ueda et al., 2018).

5.10 Conclusion

The FlySpotter could assist and lighten the taxonomy/identification of Diptera species. It also encourages citizen scientists to take part in exploring the diversity of the dipteran fauna and data collection, but further development is needed to make this app better.

5.1 Chapter summary

Results from this work have demonstrated that the integration of mobile technology and machine learning into species identification is a promising development, especially for regions where traditional taxonomic resources are scarce. While taxonomic challenges remain, localized, AI-driven tools for Diptera identification can support education, research, and conservation. Their deployment complements global efforts such as the global taxonomy initiative and aligns with international biodiversity and sustainability goals.

Chapter 6

Dissertation Synthesis: General Discussion, Conclusions, and Recommendations.

6.1 Chapter introduction

This study started with a systematic review on the taxonomic developments, distribution, endemism, and economic impact of AD aimed, then an experimental work to assess the composition and diversity of Diptera species across different habitats and seasons in MNP, Zimbabwe, and developed and evaluated a mobile application that can be used in the identification of AD species, as outlined in 1.4. This chapter summarizes the results and synthesizes the findings.

6.2 Summary of objective outcomes

6.2.1 Review of literature on taxonomic developments, distribution, endemism, and economic impact of AD

Chapter 3 examined the body of knowledge regarding dipterans through a literature review. The major findings indicated that Diptera research has been hindered by taxonomic impediments. In light of this, molecular techniques, together with the creation of eDNA, have been employed to identify Diptera species using their DNA sequences. The techniques have been successful in many ways, including separating closely related species that could have been close to impossible to separate morphologically. Many taxonomic revisions are using molecular techniques. However, the techniques are still expensive and require a high level of expertise, together with sophisticated technologies that are lacking in developing countries like Zimbabwe. As such, traditional methods have remained the cornerstone for species identification in research work. Despite the emerging technologies like machine learning, Google Teachable Machine in particular, less work has been devoted to explore its power to solve taxonomic challenges. The few studies that have used Google Teachable Machine achieved amazing results > 95% in most cases. Therefore, if harnessed properly, ML can be an alternative tool in revolutionizing Diptera identification, alongside DNA barcoding.

Despite recent literature pointing to important Diptera roles in pollination services, decomposition, and an alternative source of fish food, the bulk of the literature on Diptera species focuses on vectors, pests, and parasitology. The co-occurrence of keywords was dominated by vectors and diseases such as malaria, and trypanosomiasis. As such, pollinator network studies should focus on exploring dipteran pollination in both croplands and protected areas. As recent literature in South Africa has demonstrated interesting roles of Diptera in pollination than ever before, with Syrphidae being considered the second largest group of pollinators after honey bees. These results are coming at time when colon disorder is causing the world's decline of honey bee populations, hence the ubiquitous nature of Diptera species can give hope to farmers and agronomists.

Review of literature also demonstrated that South Africa is the hotspot for both endemic and Diptera species than any other country in the Afrotropical region. This has been alluded to the fact that South Africa has a considerably larger number of taxonomists, curators, and dipterists than in the region. Therefore, a high number of publications have been produced in that country.

6.2.2 Sampling of Diptera in MNP, and the influence of season, habitats, and year on abundance, richness, and diversity

The study produced results that will contribute to the scientific body of knowledge, as no study has been conducted dipterans in MNP. The total number of Diptera individuals sampled was 1,838. Of the total, 94 genera belonging to 29 families were identified. It is from these that 58 dipterans were identified to species level, belonging to 15 families. The most abundant genera were *Minettia* sp, *Anthomyia* sp, *Cosmina* sp, *Musca* sp, and *Dichaetomyia* sp, but the least dominant included *Asarkina* sp and *Billaea* sp.

Furthermore, species richness and Shannon diversity varied across habitat type, seasonality, and year. The highest species richness was significantly reported during the hot-wet season, but the lowest richness was in the hot-dry season. Species diversity, on the contrary, peaked during the hot-dry seasons, but it dropped during the cool-dry seasons. Species abundance, richness, and diversity varied across habitats in MNP, with grasslands having the highest species abundance, richness, and diversity, while species abundance and richness were lowest in woodlands, and species diversity was lowest in mountain habitats. These metrics also varied across the sampling years, with 2022 having the highest species abundance, richness, and diversity, however species abundance and richness was lowest in 2025 and species diversity being lowest in 2024. However, future studies should try to use other sampling techniques like baiting, light traps, and malaise traps to try other species that were not captured by pan traps.

6.2.3 Development of a mobile application

The developed mobile application (FlySpotter) successfully identified 30 species used in the training when tested, demonstrating the power of machine learning in learning and predicting species. There is, however, a need to look for funding to develop this work further, to increase the representation of species, add the offline mode, automatically log metadata, and create partnerships with Zimbabwe parks and the Museum. In resource-limited countries like Zimbabwe, these mobile applications if trained properly, can revolutionize Diptera identification. The need to have such an innovative mobile application is necessitated by the scarcity of dipterists in Zimbabwe, which resulted in specimens collected during this study being identified outside Zimbabwe (Tanzania), with some remaining unidentified or identified to family and genus level only.

Furthermore, nothing is known about the full list of species found in MNP, and their ecology, yet this little study revealed that the Diptera are changing a lot in MNP, hence, the need for a mobile application to have enhanced identification skills.

6.4 Contribution to education 5.0: innovation and industrialization

This project aligns with education 5.0, a heritage-based educational philosophy that focuses on innovation and industrialization, moving beyond traditional teaching, research, and community service to include innovation and industrialization as key components (Mutseekwa, 2024). This work demonstrated the power of low-coding models in predicting species in resource-limited countries. Having illustrated its potential to increase participation by untrained people in data collection and curation, it is undoubtedly a significant step in fulfilling the expectations of the Zimbabwean Education 5.0 policy. This work supports several SDGs: 4 (Quality education), 9 **(**Industry, Innovation, and Infrastructure**)**, 13 (Climate Action)**,** and 15 (Life on Land). It supports SDGs 9 and 15 by showing how innovative digital tools can enhance species identification and biodiversity monitoring. With less than a quarter of Diptera currently described, and many at the brink of extinction before discovery and description, traditional identification methods alone are not enough. The inclusion of AI-based tools such as GTM into species identification offers an effective alternative support to global taxonomic efforts. This work contributed to the Global Taxonomy Initiative by supporting rapid, accessible identification, especially for orders like Diptera that are often overlooked due to negative public perception. Furthermore, the application has educational value (SDG 4), as it educates the youth and the public to learn about insect ecology. The application is under the process of registration for the protection of the name.

6.5 Recommendations

To strengthen the knowledge and conservation of Diptera biodiversity, future studies should implement an expanded sampling strategy incorporating Malaise traps, light traps, sweep netting, and other complementary techniques to capture species not attracted to pan traps. Further, conservation agencies and NGOs should prioritize training programs for conservationists, environmentalists, and community members to raise awareness of the critical but often overlooked role of dipteran pollination in both wild and agricultural ecosystems. Taxonomists and museum curators should actively integrate new technologies AI and ML into their workflows to propel species identification, enabling the rapid development of comprehensive Diptera inventories and checklists for all protected areas/national parks in Zimbabwe. These baseline surveys and species documentation efforts should form the foundation for long-term monitoring programs, allowing early detection of population changes and providing robust data to guide evidence-based conservation planning and policy

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Appendix 1: The abundance of the identified individuals to the species level.

Families	Species	Abundance	Proportion %
Asilidae	*Oligopogon nitidus*	15	2.697
	Dichaetothyrea calvifrons	4	0.719
	Clinopogon unicolo	5	0.899
Anthomyiidae	*Anthomyia pluvialis*	5	0.899
Bombyliidae	*Bombomyia discoidea*	5	0.899
	Bombylius discolor	3	0.539
	Geron prosopidis	1	0.179
Calliphoridae	*Mafikengia ciliata*	1	0.719
	Chrysomya megacephala	2	0.359
	Bengalia aliena	45	8.093
	Pericallimyia westermanni	1	0.179
Curtonotidae	*Curtonotum uncinatum*	8	1.438
Ephydridae	*Ochthera cuprilineata*	9	1.618
Muscidae	*Musca domestica*	33	5.935
	Atherigona varia	11	1.978
	Coenosia karli	12	2.158
	Lipse paraspila	46	8.273
	Helina protuberans	1	0.179
	Dichaetomyia tanovata	9	1.618
	Pyrellia rapax	10	1.798
	Dichaetomyia latistriata	17	3.057
	Dichaetomyia latiorbitalis	20	3.597
	Musca confiscata	6	1.079
Nemestrinidae	*Stenobasipteron wiedemanni*	2	0.359
Platystomatidae	*Bromophila caffra*	4	0.719
	Rivellia asiatica	5	0.899
	Rivellia alini	2	0.359
Rhiniidae	*Isomyia singhi*	7	1.258
	Isomyia viridaurea	20	3.597
	Isomyia electa	15	2.697
	Isomyia facialis	1	0.179
	Cosmina limbipennis	39	7.014
	Stegosoma bowdeni	1	0.179
Sarcophagidae	*Sarcophaga africa*	39	7.014
	Metopia campestris	39	7.014
	Miltogramma germari	25	4.496

Stratiomyidae	*Adomyia palaestinensis*	1	0.179
	Hermetia illucens	2	0.359
Syrphidae	*Eumerus aurfrons*	11	1.978
	Toxomerus floralis	1	0.179
	Asarkina amoena	1	0.179
	Paragus longiventris	2	0.359
	Phytomia incisa	3	0.539
	Paragus minutus	6	1.079
	Syritta flaviventris	1	0.178
	Paragus borbonicus	2	0.539
	Paragus capricorni	4	0.719
	Mesembrius capensis	1	0.178
	Eumerus paulae	1	0.178
Tabanidae	*Haematopota bigoti*	3	0.539
	Atylotus rusticus	4	0.719
	Atylotus latistriatus	2	0.359
Tachinidae	*Dejeania bombylans*	4	0.719
	Oxymedoria palpata	1	0.178
	Diaprochaeta illustris	1	0.178
	Billaea fortis	1	0.178
	Musca xanthomelaena	16	2.878
	Dyshypostena tarsalis	4	0.719
Total		**556**	**100%**

Appendix 2: The abundance of the identified individuals at the genus level.

Genus	Abundance	Percentage
Adelidea	6	0.639
Adomyia	1	0.106
Aedeomyia	2	0.213
Afrodomia	1	0.106
Alcimus	1	0.106
Anthomyia	38	4.051
Apiocera	3	0.319
Asarkina	1	0.106
Atherigona	11	1.172
Atylotus	6	0.639
Bengalia	46	4.904
Billaea	1	0.106
Bombomyia	5	0.533

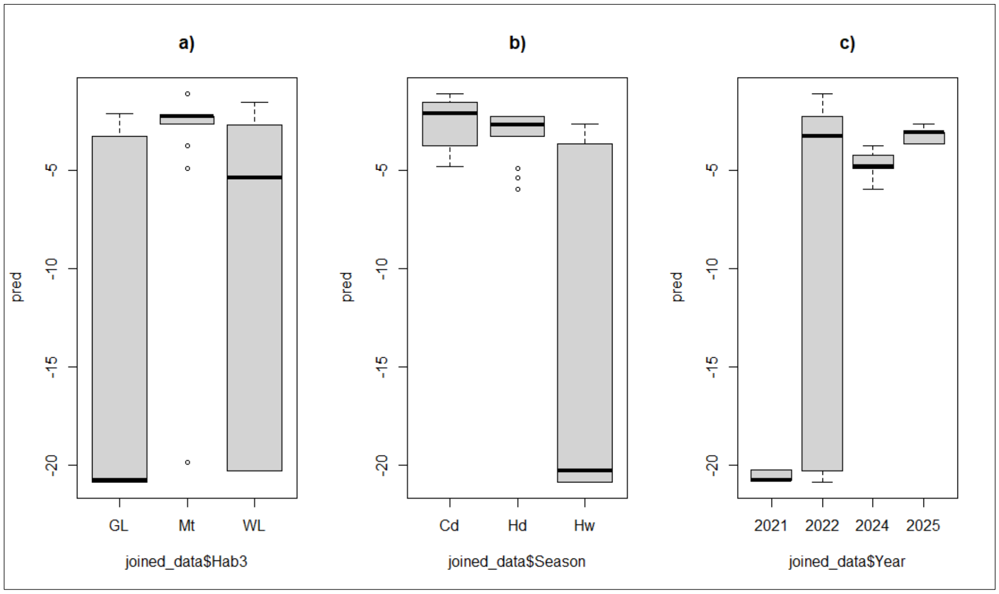
Genus	Abundance	Percentage
Bombylius	3	0.319
Boreoheptagyia	3	0.319
Bracheliopsis	7	0.746
Bromophila	4	0.426
Chaetodiopsis	3	0.319
Chromatophania	1	0.106
Chrysomya	2	0.213
Cladoderris	2	0.213
Clinopogon	3	0.319
Coenosia	12	1.279
Cosmina	39	4.157
Curtonotum	8	0.852
Dejeania	4	0.426
Diaprochaeta	1	0.106
Dichaetomyia	51	5.437
Dichaetothyrea	4	0.426
Dilophus	1	0.106
Diopsis	5	0.533
Dischistus	1	0.106
Dolichopodidae	1	0.106
Dyshypostena	4	0.426
Emerus	3	0.319
Empis	1	0.106
Epaemoides	16	1.705
Ethilla	22	2.345
Eumerus	10	1.066
Eurycarenus	12	1.279
Exorista	1	0.106
Furcamyia	2	0.213
Geron	1	0.106
Glyphodera	1	0.106
Haematopota	3	0.319
Heligmonevra	2	0.213
Helina	32	3.411
Hemigephyra	4	0.426
Hermetia	1	0.106
Heterotropus	3	0.319
Hyleorus	8	0.852

Genus	Abundance	Percentage
Isomyia	43	4.584
Limnophora	19	2.025
Lipse	46	4.904
Mafikengia	1	0.106
Mesembrius	1	0.106
Mesolaptogaster	1	0.106
Mesoleptogaster	6	0.639
Metopia	39	4.157
Microsargus	1	0.106
Miinettia	1	0.106
Miltogramma	25	2.665
Minettia	59	6.289
Musca	60	6.396
Ochthera	9	0.959
Oligopogon	15	1.599
Oxymedoria	1	0.106
Pachycerina	1	0.106
Palintonus	2	0.213
Paragus	15	1.599
Pericallimyia	1	0.106
Perisiella	9	0.959
Phumosia	23	2.452
Phytomia	3	0.319
Platyschineria	19	2.025
Promachus	9	0.959
Pyrellia	10	1.066
Rhipidocephala	1	0.106
Rhyncomyia	37	3.944
Rivellia	10	1.066
Salentia	6	0.639
Sarcophaga	40	4.264
Sciara	5	0.533
Sisyropa	2	0.213
Stegosoma	1	0.106
Stenobasipteron	2	0.213
Syritta	1	0.106
Systochus	3	0.319
Tabanus	1	0.106

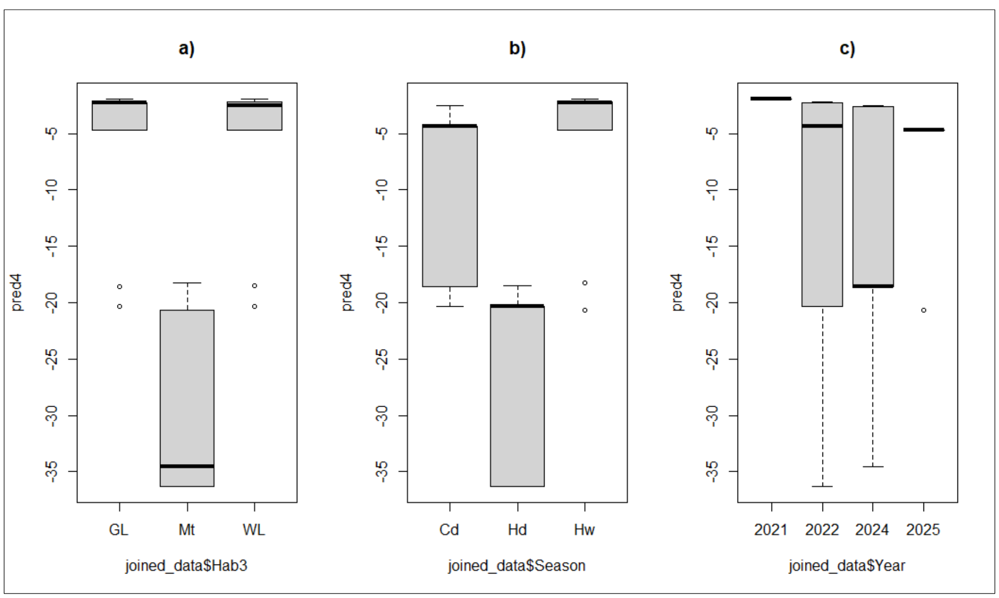
Genus	Abundance	Percentage
Tephritidae	1	0.106
Tomosvaryella	2	0.213
Toxomerus	1	0.106
Tropicomyia	1	0.106
Zelamyia	2	0.213
Adelidea	6	0.639
Adomyia	1	0.106
Aedeomyia	2	0.213
Afrodomia	1	0.106
Alcimus	1	0.106
Anthomyia	38	4.051
Apiocera	3	0.319
Asarkina	1	0.106
Atherigona	11	1.172
Atylotus	6	0.639
Bengalia	46	4.904
Billaea	1	0.106
Bombomyia	5	0.533
Bombylius	3	0.319
Boreoheptagyia	3	0.319
Bracheliopsis	7	0.746
Bromophila	4	0.426
Chaetodiopsis	3	0.319
Chromatophania	1	0.106
Chrysomya	2	0.213
Cladoderris	2	0.213
Clinopogon	3	0.319
Coenosia	12	1.279
Cosmina	39	4.157
Curtonotum	8	0.853
Dejeania	4	0.426
Diaprochaeta	1	0.106
Dichaetomyia	51	5.437
Dichaetothyrea	4	0.426
Dilophus	1	0.106
Diopsis	5	0.533
Dischistus	1	0.106
Dolichopodidae	1	0.106

Genus	Abundance	Percentage
Dyshypostena	4	0.426
Emerus	3	0.319
Empis	1	0.106
Epaemoides	16	1.705
Ethilla	22	2.345
Eumerus	10	1.066
Eurycarenus	12	1.279
Exorista	1	0.106
Furcamyia	2	0.213
Geron	1	0.106
Glyphodera	1	0.106
Haematopota	3	0.319
Heligmonevra	2	0.213
Helina	32	3.411
Hemigephyra	4	0.426
Hermetia	1	0.106
Heterotropus	3	0.319
Hyleorus	8	0.852
Isomyia	43	4.584
Limnophora	19	2.025
Lipse	46	4.904
Mafikengia	1	0.106
Mesembrius	1	0.106
Mesolaptogaster	1	0.106
Mesoleptogaster	6	0.639
Metopia	39	4.157
Microsargus	1	0.106
Miinettia	1	0.106
Miltogramma	25	2.665
Minettia	59	6.289
Musca	60	6.396
Ochthera	9	0.959
Oligopogon	15	1.599
Oxymedoria	1	0.106
Pachycerina	1	0.106
Palintonus	2	0.213
Paragus	15	1.599
Pericallimyia	1	0.106

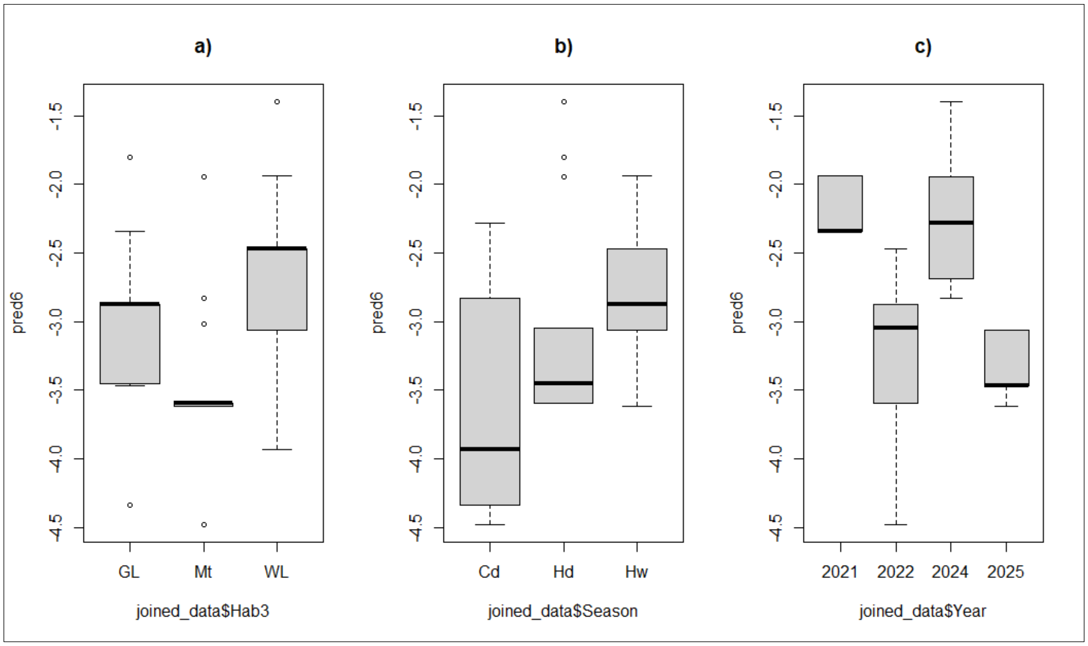
Genus	Abundance	Percentage
Perisiella	9	0.959
Phumosia	23	2.452
Phytomia	3	0.319
Platyschineria	19	2.025
Promachus	9	0.959
Pyrellia	10	1.066
Rhipidocephala	1	0.106
Rhyncomyia	37	3.944
Rivellia	10	1.066
Salentia	6	0.639
Sarcophaga	40	4.264
Sciara	5	0.533
Sisyropa	2	0.213
Stegosoma	1	0.106
Stenobasipteron	2	0.213
Syritta	1	0.106
Systochus	3	0.319
Tabanus	1	0.106
Tephritidae	1	0.106
Tomosvaryella	2	0.213
Toxomerus	1	0.107
Tropicomyia	1	0.107
Zelamyia	2	0.214



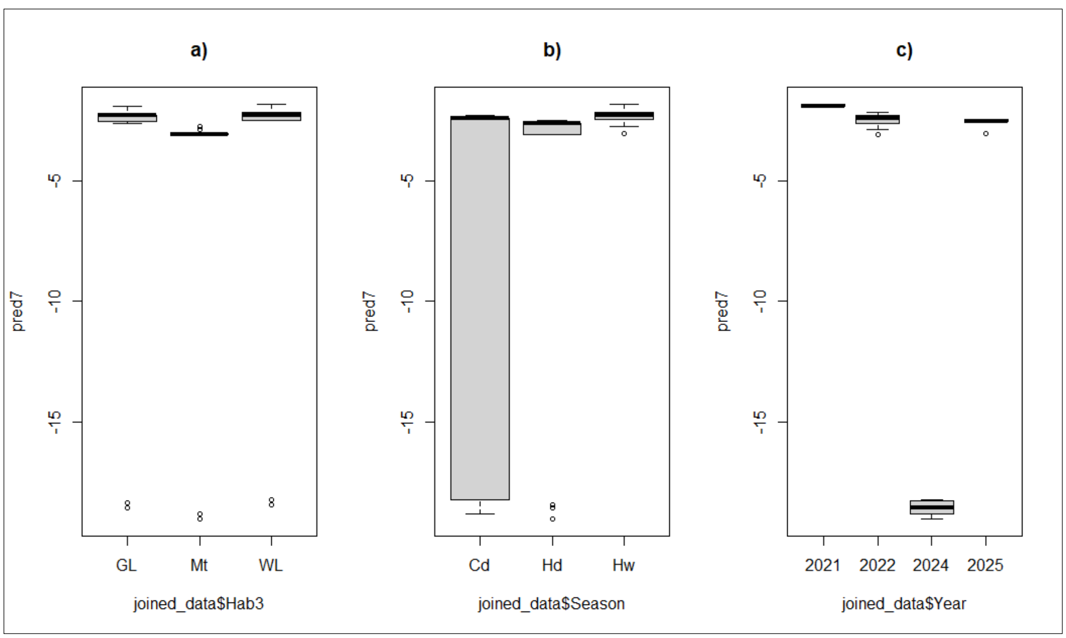
Appendix 3. The predicted probability of Anthomyiidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



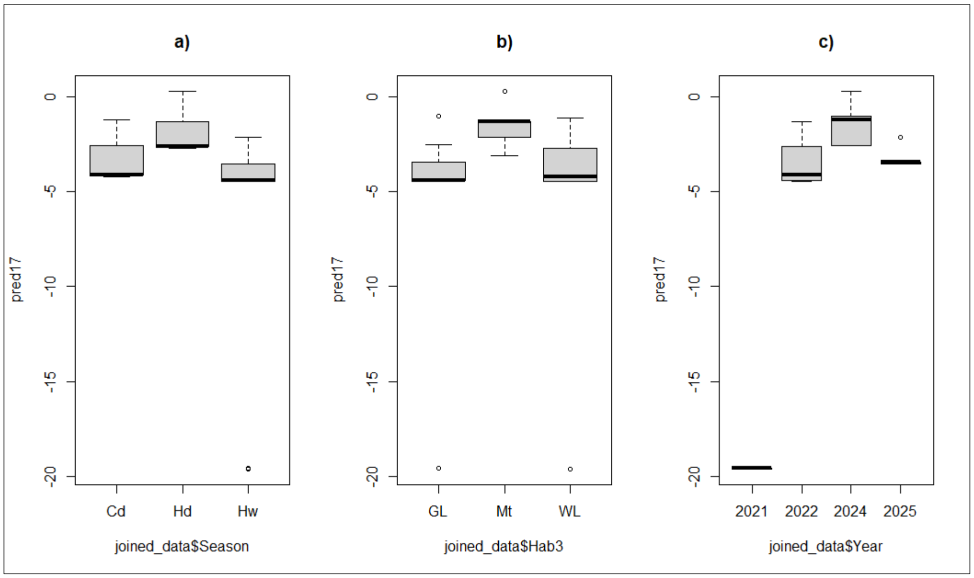
Appendix 4: The predicted probability of Asilidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



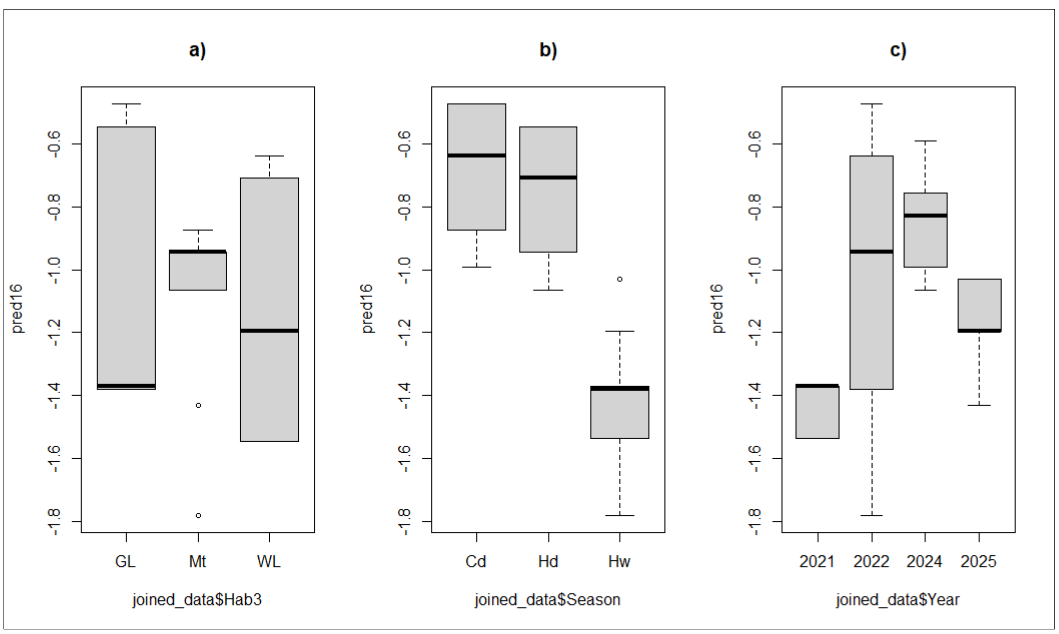
Appendix 5: The predicted probability of Bombyliidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



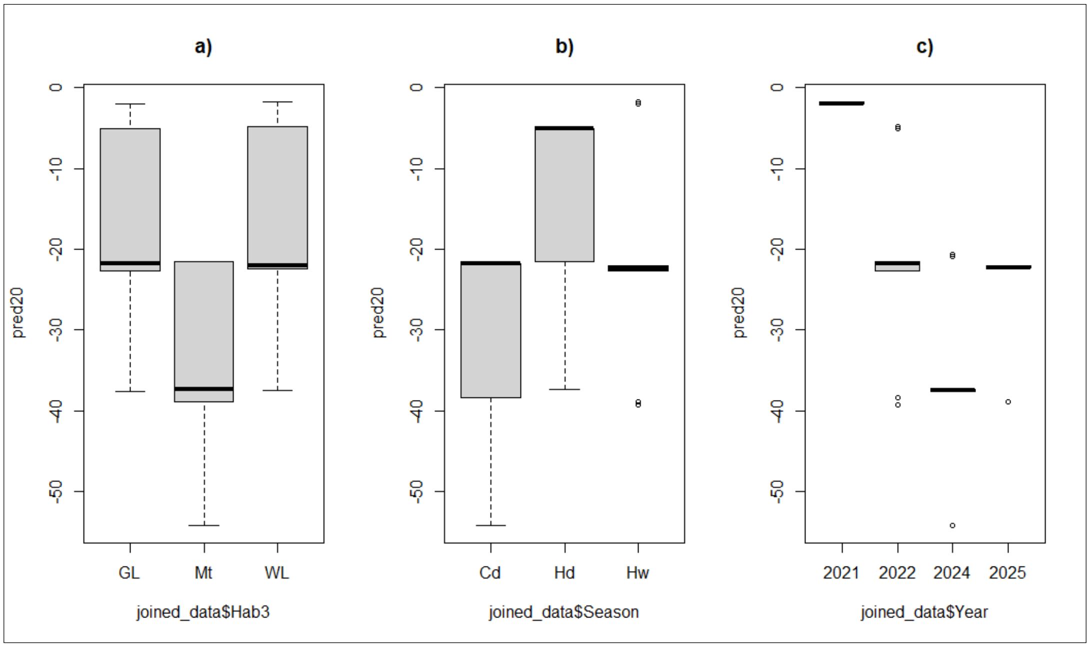
Appendix 6: The probability of Calliphoridae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



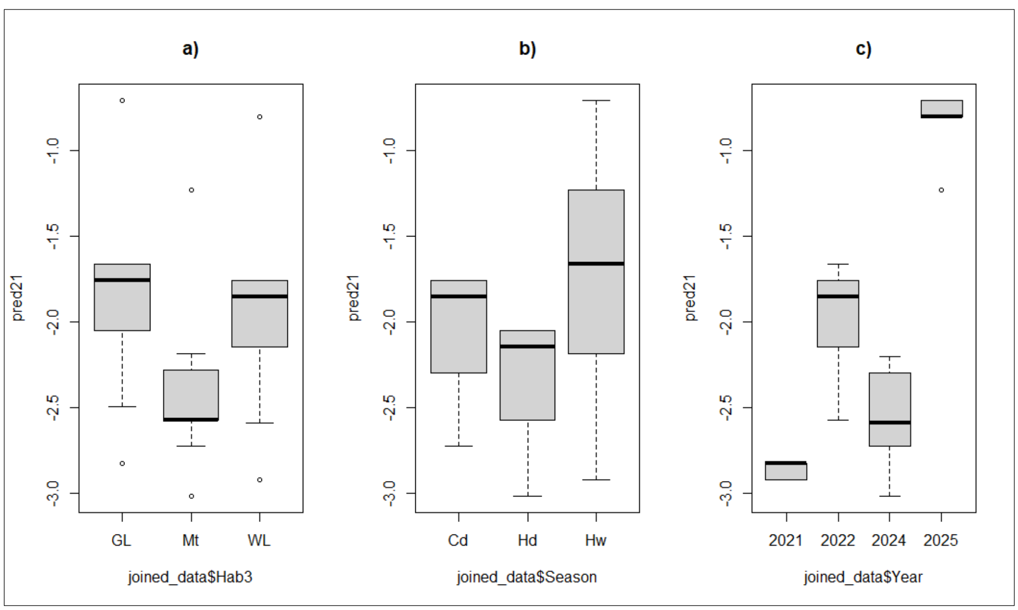
Appendix 7: The probability of Lauxaniidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



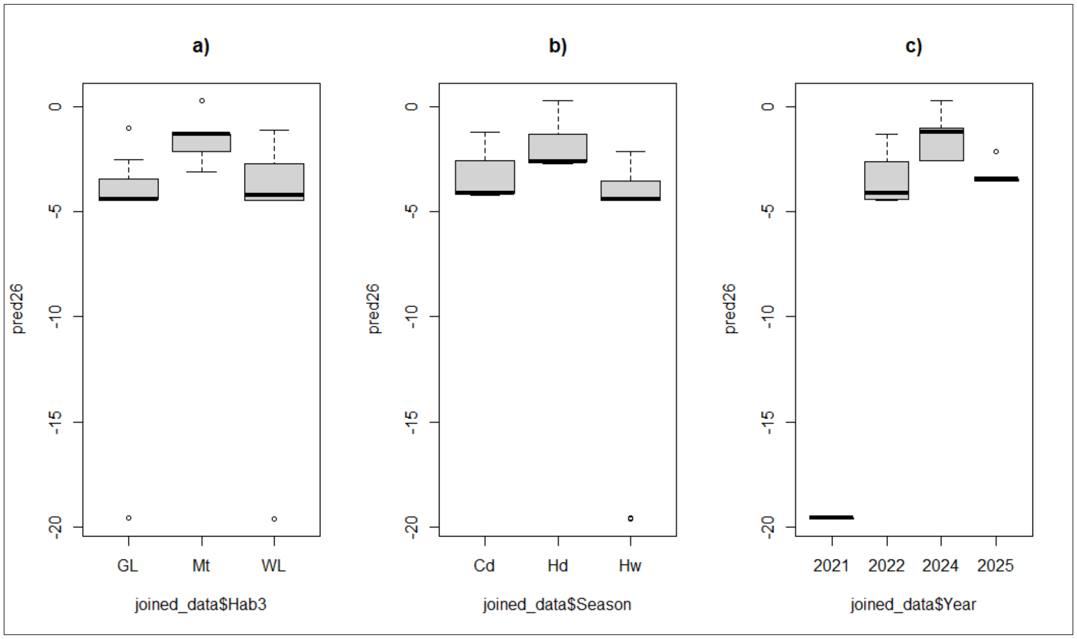
Appendix 8: The probability of Muscidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



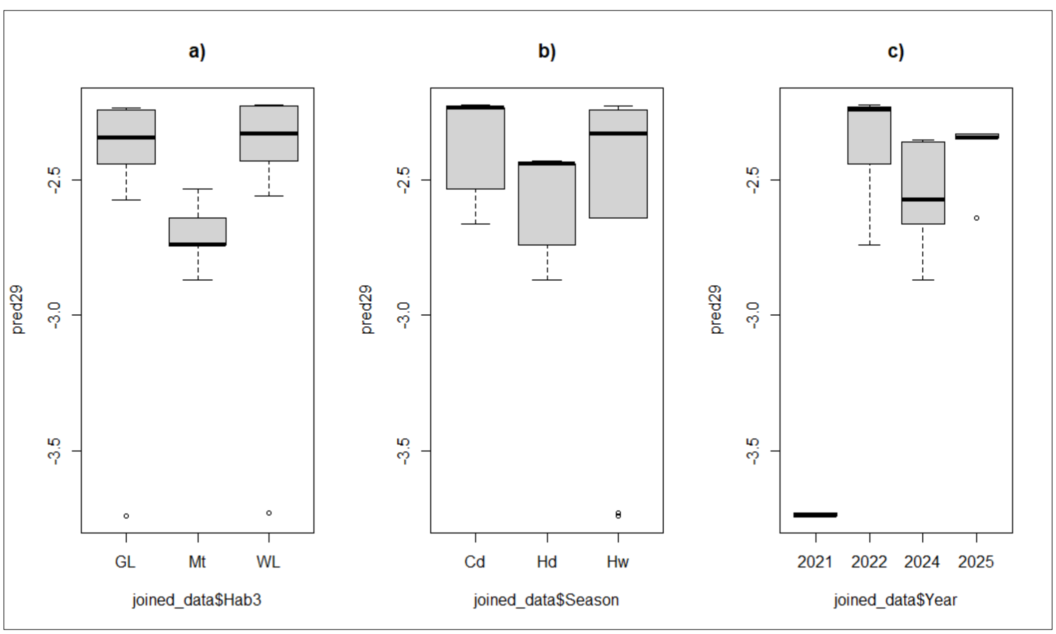
Appendix 9: The probability of Platystomatidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



Appendix 10: The probability of Rhiniidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



Appendix 11: The probability of Tabanidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.



Appendix 12. The probability of Tachinidae occurrence across habitats, seasons, and years. **GL** = Grasslands, **Mt** = Mountains, **WL** = Woodlands. **Cd** = Cool-dry season, **Hd** = Hot-dry, **Hw** = Hot-wet.

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