DOI: 10.1002/2688-8319.12178

# **RESEARCH ARTICLE**



# Pollinator efficiency of avocado (Persea americana) flower insect visitors

# Ingolf Steffan-Dewenter<sup>2</sup> | H. Michael G. Lattorff<sup>1,3</sup>

<sup>1</sup>International Centre of Insect Physiology and Ecology (icipe), Nairobi, Kenya

<sup>2</sup>Department of Animal Ecology and Tropical Biology, Biocenter University of Würzburg, Würzburg, Germany

<sup>3</sup>Department of Chemistry, University of Nairobi, Nairobi, Kenya

#### Correspondence

Rose Nyakemiso Sagwe, International Centre of Insect Physiology and Ecology (icipe), PO Box 30772-00100, Nairobi, Kenva, Email:namikorose@yahoo.co.uk rsagwe@icipe.org

Handling Editor: Harriet Downey

#### **Funding information**

Deutsche Gesellschaft für Internationale Zusammenarbeit, Grant/Award Number: 17,7860,4-001

Rose Nyakemiso Sagwe<sup>1,2</sup> 💿 🕴 Marcell K. Peters<sup>2</sup> 💿 🕴 Thomas Dubois<sup>1</sup>

### Abstract

- 1. Pollination services from insects are important for higher yield and better fruit quality in avocado (Persea americana Mill.). Measuring pollinator effectiveness is significant for capturing the relative contributions of different insect taxa to pollination services and for identification of the most important pollinators of this globally important crop.
- 2. In the present study, we tested pollinator efficiency of avocado in Kenya based on pollen deposition after single visits of flowers by different pollinator species and visitation frequency. We monitored the pollination frequency during the flowering period replicated across six farms. Three trees were selected per farm, each with five flower panicles.
- 3. Out of the 14 observed insect flower visitor species, pollen deposition efficiency was highest in the Western honey bee (Apis mellifera L.), followed by the hover fly species (Phytomia incisa W.). These two species had both the highest pollen deposition and pollen grain loads on their bodies.
- 4. Furthermore, A. mellifera was the most frequent avocado flower visitor followed by Diptera except hoverflies.
- 5. Our results imply that A. mellifera can be managed to achieve adequate pollination services for avocado, particularly in areas lacking efficient wild pollinators.

### KEYWORDS

crop pollination service, flower visitation, pollen deposition, pollination efficiency, pollinator management

# 1 | INTRODUCTION

Insect-mediated pollination is an important ecosystem service for food security, agrobiodiversity, and ecosystem resilience (Garibaldi et al., 2014). Pollinator conservation within agricultural regions is essential

because crops require wild or managed pollinators, especially in intensive agricultural regions, to attain maximum yields (Lye et al., 2011). However, insect pollination is threatened by several environmental and anthropogenic factors. Concerns have been raised over a looming pollinator crisis caused by loss of habitat, climate change and intrusion

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2022 The Authors. Ecological Solutions and Evidence published by John Wiley & Sons Ltd on behalf of British Ecological Society.

by alien species (Dicks et al., 2021; Potts et al., 2010). Therefore, the understanding and conservation of the importance of pollinator diversity is important to support the increasing demand for food (Burkle & Alarcón, 2011). Most flowering crops are visited by a variety of insects but their contribution to pollination remains unknown. A flower visitor is considered a pollinator when it transfers and deposits conspecific pollen grains on the stigma (Fumero-Cabán & Meléndez-Ackerman, 2007). Therefore, distinguishing pollinators from other flower visitors is of utmost importance for management of the pollinator species.

Several insects provide pollination services but the Western honey bee (Apis mellifera L.) has been considered as the most important pollinator of many crops worldwide by increasing fruit set, seed production, crop yield, and crop quality (Greenleaf & Kremen, 2006; Winfree et al., 2007). Managed A. mellifera may partially offset non-managed pollination services and compensate for the loss of wild pollinators, although A. mellifera is feral in West and East-Africa and some areas of the world (Sagwe et al., 2021). However, it is important to know the actual performance of individual pollinator species for possible selection as candidates for the introduction of managed pollinators (Thapa, 2006). Some studies have shown that wild insects can be effective pollinators and cannot be completely substituted by managed pollinators (Jauker et al., 2012). For instance, in oilseed rape (Brassica napus), coffee (Coffea arabica), onion (Allium cepa), almond (Prunus dulcis), tomato (Solanum lycopersicum) and strawberry (Fragaria ananassa), wild pollinators have been reported to be more effective than honey bees in terms of fruit set (Garibaldi et al., 2013; Klein et al., 2003; Rader et al., 2016).

In our previous study, we assessed the dependence of avocado fruit set on insect pollination. Our results demonstrated that avocado depends on insects for pollination. There was a significantly higher fruit set on insect-pollinated flowers (89.5%) than wind pollination and spontaneous selfing (17.4%) and autogamous self-pollination (6.4%) as referenced to the control (hand pollination-100%) (Sagwe et al., 2021). Collection time (time of visitation), visitation time, and pollen deposition are key factors for measuring pollination efficiency of insects in crops (Fishbein & Venable, 1996). Various methods have been used to measure pollination efficiency, for instance, measuring fruit or seed set after flower visitation, measuring pollen load on pollinators and their pollen deposition onto stigmas or measuring plant reproductive success post-pollination (Ne'eman et al., 2010). On the other hand, the abundance of flower visitors has been used as a proxy to estimate pollination services and crop yield (Dainese et al., 2019; Zou et al., 2017). Therefore, understanding how managed bees and wild pollinators differ in pollination efficiency is important for current and future crop production.

In the present study, we used avocado (*Persea americana* Mill.) as a model crop to quantify the pollination efficiency of different insect species in Kenya. In Kenya, avocado is widely grown and has been a major part of horticultural earnings (Amare et al., 2019), with 368,370 metric tonnes produced annually valued at 639 million USD (HCDA, 2017). Kenya is currently ranked sixth in avocado export volumes after Peru, Chile, South Africa, Israel, and Mexico (HCDA, 2017). Avocado is an exotic crop in Africa, originating from Southern Mexico. A study by Ish-am et al. (1999) in Mexico identified stingless bees (Meliponini) and the Mexican honey wasp (*Brachygastra mellifica*) as the primary avocado pollinators, while in Southeast Spain and Israel, bumble bees (*Bombus terrestris*) have been reported as an efficient avocado pollinator (Ish-Am & Eisikowitch, 1993; Wysoki et al., 2002). However, in East Africa, where smallholder farming systems are commonly practiced, there is a lack of data on pollination efficiency for avocado. Measuring pollinator efficiency of avocado flowers is thus important for capturing the relative contributions of different insect taxa to pollination services to maximize production.

Avocado has a unique flowering pattern known as a protogynous dichogamy, whereby the flowers are hermaphroditic (have both male and female parts) but open as female and male separately at different times. Due to their flowering sequence, the avocado cultivars are grouped into two categories: 'A-type' and 'B-type'. In 'A-type' cultivars, flowers commonly open as functionally female in the morning of the first day and as functionally male in the afternoon of the second day, whereas in 'B-type' cultivars, flowers are commonly female in the afternoon of the first day and male in the morning of the second day (Ish-Am & Lahav, 2011). This process is a mechanism that encourages cross-pollination (Ish-Am & Eisikowitch, 1998). Therefore, a lack of pollinators (pollen vectors) can seriously limit fruit formation and reduce crop yields (Alcaraz & Hormaza, 2009).

This study investigated the pollen deposition efficiency of different avocado flower visitors. Specifically, we analysed the performance of flower visitors by determining stigmatic pollen deposition per single visit to assess their efficiency as pollen-transfer agents. In addition, we evaluated the amount of pollen on the insect body, flower handling time (visitation time) and visitation frequency as additional parameters for pollination efficiency.

### 2 | MATERIALS AND METHODS

### 2.1 Study site

The study was carried out in smallholder avocado farms in Murang'a County, Kenya (S 0°43'0", E 37°9'0"). Two avocado varieties were grown in the orchards: Fuerte and Hass. The experiments were conducted during August–October 2019, which encompasses the major avocado blooming period in Kenya. Six smallholder avocado farms (0.2–0.4 ha) were selected for the study. The farms had similar management practices with no application of pesticides; furthermore, the farms were selected such that they were at a distance of at least 3.5 km from farms with bee hives based on the foraging distance for bees (Visscher & Seeley, 1982) and with similar distances from the natural forests.

### 2.2 | Visitation frequency

Visitation frequency is the number of pollinators visiting a flower per unit time which is a variable used to assess insect pollination and its

contribution to plant reproduction (Bergamo et al., 2016). On each farm, three trees spaced 20 m apart were randomly selected for the experiment. Selected trees were spaced a minimum of 10 m from the edge of the farm to minimize edge effects. On each tree, three branches with at least five flower panicles (clusters) were randomly selected. The flowers surveyed were at a height between 0.5 and 2 m above ground. Flower visitors were observed and recorded at 30 min intervals between 8:00 AM and 5:00 PM and this was done per farm. A 'visit' was recorded if the insect contacted the reproductive structures, and each individual insect was only counted once. Pollinator surveys were conducted exclusively during sunny days without rain and minor wind. We conducted farm-based flower visitor observations nine times with each farm visited once a month for a period of 3 months. We used direct observation in the field to group the avocado flower visiting insects into the following taxa: Western honey bee (A. mellifera), hover flies (Syrphidae), 'other flies' (Diptera, except for Syrphidae), wasps (Vespidae), butterflies (Lepidoptera), wild bees (Apidae, except A. mellifera) and beetles (Coleoptera).

# 2.3 | Quantifying pollination efficiency: Single-visit pollen deposition

Single-visit deposition (SVD) data were collected for comparison to measure pollinator efficiency (Ne'eman et al., 2010). Following the method of Huda et al. (2015), in the afternoon before the data collection day, 32 panicles per farm in three farms with flower buds were randomly selected and bagged with fine woven bags that were impermeable to wind and excluded pollinators. The bag was carefully removed the following morning from each panicle when the flowers had opened. Virgin stigmas were identified on flowers that had opened overnight using a hand lens and were marked. Individual flowers were observed until they received their first visitor after unbagging the panicles. Pollinators were caught on their first visit as they exited the flowers. The length of stay (flower handling time) was measured using a stopwatch from the moment the insect started to forage on the flower until the moment the insect left it. Insects were always allowed to complete their visit before being captured using a sweep net. Flower visitors were placed in individual vials for later morphological identification to species level. The survey continued each day until there were no more bagged flowers left to sample or the visitation rate had decreased to a low level (no visits recorded for 1 h) per farm. Once the panicles were unbagged and the open flowers received visitors, they were not re-bagged unless that panicle was not visited. Control stigmas were removed from newly uncovered virgin flowers before a visit took place to account for pollen found on stigmas due to opening of the flower and/or handling and bagging procedures. The stigmas of visited flowers and control flowers were sampled, put in individual 0.5-ml vials with 70% ethanol and stored in a cooler box at  $-18^{\circ}$ C. Samples were subsequently transported to the laboratory for pollen count analysis. The study was conducted for a period of 9 days and 3 days of bagging and preparation.

# 2.4 | Palynological analyses

The quantity of pollen carried on insects' bodies was estimated using the method described by Krause and Wilson (1981). In the laboratory, 0.5 ml of distilled water was added to the vials with captured insects and vials were shaken vigorously until no more pollen could be seen on their body after which centrifugation was done to remove the excess water/supernatant. The insects were then transferred into vials containing 0.5 ml of 70% ethanol for identification. Before washing off the pollen from the insects, the bee corbiculae were removed to avoid sampling of corbicula pollen since they are not available for pollination. The pollen grains were stained using Fuchsin glycerine jelly and were counted using a microscope at 100× magnification.

In the laboratory, the stigmas were crushed on a microscope slide and stained with fuchsin–glycerine jelly as described by Beattie (1971). All conspecific (avocado pollen grains) and heterospecific (non-compatible with avocado pollen grains) pollen grains deposited were counted under a light microscope.

# 2.5 | Statistical analysis

Differences in averages of visitation frequency among pollinators at different times of the day were analysed using linear mixed-effects models (LMM) using the R package Ime4 (Bates et al., 2015). The observational date and farm ID was used as a random factor to account for the non-independence in visitation frequency data due to multiple measurements per farm and observation day. Means separation was performed using the Ismeans package (Lenth, 2016), and significant differences were generated using the multcompview package (Graves et al., 2019). Visitation frequency measures at different times across the same day were considered as repeated measures, accounted for by adding date as a random intercept term to mixed-effects models. Visitation frequency was the response variable, while flower visitors and time were the explanatory variables. SVD for different species was quantified by counting the number of conspecific pollens on flowers of avocado, which is a direct measurement of successful pollination per individual visit. Heterospecific pollen was also counted and analysed using LMM to determine the difference in heterospecific pollen carried and deposited among the insect species; sampling date and farm ID was used as a random factor. Pollen deposition efficiency was taken as the number of compatible pollen grains deposited on the stigma after a single visit. LMMs were used to determine the difference in SVD of pollen among the insect species and the amount of compatible pollen on the insect body. In this analysis, sampling date and farm ID was used as a random factor. Likewise, the flower handling time data were subjected to LMM to evaluate whether pollinator species differed in flower handling time; observational date and farm ID wer used as a random factor. Pearson's correlation analysis based on the means per species was used to establish the linear relationship between pollen on the insect body and pollen deposited on the stigma. Pearson's correlation analysis was also used to evaluate whether there was a relationship between **TABLE 1** The relative abundance and visitation frequency (visits/30 min/flower) of flower visitors (*n* = 605) across smallholder avocado farms in Murang'a County, Kenya

Flower visitor	Relative abundance (%)	Visitation frequency (visits/30 min)
Western honey bee (Apis mellifera)	55	$2.18\pm0.22^{c}$
Diptera, except for Syrphidae ('other flies')	16	$0.63\pm0.10^{\rm b}$
Hover flies (Syrphidae)	11	$0.44\pm0.07^{ab}$
Wasps (Vespidae)	9	$0.33 \pm 0.05^{ab}$
Wild bees (Apidae except A. mellifera)	3	$0.11 \pm 0.03^{a}$
Butterflies (Lepidoptera)	3	$0.09 \pm 0.03^{a}$
Beetles (Coleoptera)	3	$0.12 \pm 0.02^{a}$

*Note*: The values of visitation frequency are means  $\pm$  SE. Means with a different superscript letter within a column are significantly different (p < 0.05) according to Tukey test.

flower handling time, pollen on the insect body and pollen deposited on stigmas. Species that were encountered once were excluded from the analysis. All analyses were performed using R statistical software (v4.0.2, R Foundation for Statistical Computing, Vienna, Austria).

### 3 | RESULTS

# 3.1 | Flower visitor's frequency and their visitation time

Four orders (Hymenoptera, Diptera, Lepidoptera, Coleoptera) of avocado flower insect visitors were observed (n = 605), which were grouped into the following seven taxa: Western honey bee (Apis mellifera), hover flies (Syrphidae), other flies (Diptera, except for Syrphidae), wasps (Vespidae), butterflies (Lepidoptera), wild bees (Apidae except A. mellifera) and beetles (Coleoptera) (Table 1). Western honey bees were the most abundant visitors, followed by 'other flies', hover flies and wasps, while beetles, butterflies and wild bees were the least abundant (Table 1). The pollinator visitation frequency differed significantly among the different insect groups ( $F_{6, 16} = 55.34$ , p < 0.001). The highest visitation frequency per flower was found for A. mellifera, followed by other flies. There was a significant difference observed between visitation time among the different insect taxa ( $F_{6, 16} = 1.63, p < 0.001$ ). The visitation time for A. mellifera peaked during two time intervals, namely 10:30 AM to 11:30 AM and 1:30 PM to 2:30 PM. Furthermore, A. mellifera visitation was the highest throughout the observation period (9:00 AM to 5:00 PM). Hover flies were observed to be active late in the afternoon, while other flies were observed mainly at 10:30 AM to 11.30 AM (Figure S1).

### 3.2 Pollen deposition efficiency

Different pollinator species showed significantly varying abilities to carry pollen grains ( $F_{13,71} = 6.55$ , p < 0.001). Apis mellifera (Figure 1e) and Phytomia incisa W. (Figure 1b) carried relatively more conspecific pollen grains of avocado flowers (Figure S2) on their body than other

species, while relatively lowest numbers were observed in *Belonogaster* griseus Fab. (Figure 1g). There was a significant difference in pollen deposition to the stigma, that is pollen deposition efficiency, among the observed flower-visiting insect species ( $F_{13,71} = 4.54$ , p < 0.001), with *A. mellifera* and *P. incisa* showing the highest number of pollen depositions per single visit, while the lowest numbers were observed in *Chrysomya chloropyga*, *Polistes* sp. and *B. griseus* (Table 2). There was no significant difference of heterospecific pollen carried on the insect body ( $F_{13,71} = 0.31$ , p = 0.99) and those deposited in the stigma ( $F_{13,71} = 0.82$ , p = 0.64) among taxa (Table S1). There was a strong positive correlation between conspecific pollen on the insect body and conspecific pollen deposited in the stigma (Figure 2a). We calculated a ratio of 82:1 for conspecific and heterospecific pollen in stigma, while a ratio of 150:1 was calculated for conspecific and heterospecific pollen on the insect body.

# 3.3 | Flower handling time

Flower handling time varied significantly among the pollinator species  $(F_{13,71} = 2.63, p = 0.004;$  Table 2). The longest time spent on the flower was observed for *Braunsapis faveata* (Figure 1f), A. *mellifera* (Figure 1e) and *P. incisa* (Figure 1b) (Table 2). In addition, there was a positive correlation between the amount of pollen on the insect body and flower handling time and between the amount of pollen deposited and flower handling time (Figure 2b,c). Three species were excluded from the analysis because their numbers were less than three: Sphecidae (*Sceliphron* sp.), Muscidae (*Stomoxys* sp.) and Rhiniidae (*Isomyia* sp.).

# 4 DISCUSSION

Pollination efficiency, which is the relative ability of an animal to pollinate flowers successfully, is used to rank the importance of different species of flower visitors as pollinators (Ne'eman et al., 2010). After a single flower visit, pollen deposition on the stigma and the number of pollen grains on the insect body have been used previously to estimate pollination efficiency (Ne'eman et al., 2010). However, not all flower



**FIGURE 1** Examples of the avocado flower-visiting species that were evaluated regarding their pollen deposition efficiency in this study across smallholder avocado farms in Murang'a County, Kenya. (a) Syrphidae (*Eristalinus quinquelineatus*), (b) Syrphidae (*Phytomia incisa*), (c) Syrphidae (*Episerphus trisectus*), (d) Calliphoridae (*Chrysomya chloropyga*), (e) Apidae (*Apis mellifera*), (f) Apidae (*Braunsapis faveata*), (g) Vespidae (*Belonogaster griseus*), and (h) Vespidae (*Polistinae* sp.)

TABLE 2	The number of compatible pollen grains carried on the insect body, the number of compatible pollen grains deposited per single
visit/pollinati	on efficiency on the stigma of avocado flowers, and per flower handling time (duration) observed across different species in Murang'a
county, Kenya	a

Family	Species (N)	Number of pollens on insect	Number of pollens deposited/pollination efficiency	Flower handling time (s)
Apidae	Apis mellifera (41)	$282.1\pm80.8^d$	$30.9 \pm 8.5^{\circ}$	$9.2\pm0.8^{ab}$
Syrphidae	Phytomia incisa (4)	$208.3\pm54.7^{cd}$	$34.5 \pm 12.1^{bc}$	$8.0\pm0.0^{ab}$
Syrphidae	Betasyrphus hirticeps (3)	$88.3 \pm 40.2^{abcd}$	$13.0\pm4.2^{abc}$	$6.7 \pm 1.2^{ab}$
Apidae	Braunsapis faveata (3)	$85.3 \pm 9.0^{bcd}$	$16.3 \pm 1.9^{\text{abc}}$	$18.0\pm9.5^{b}$
Syrphidae	Eristalis tenax (4)	$78.0\pm23.3^{bcd}$	$6.1 \pm 2.0^{abc}$	$6.0\pm0.7^{ab}$
Syrphidae	Eristalinus quinquelineatus (4)	$72.3 \pm 24.0^{abcd}$	$12.8 \pm 4.3^{abc}$	$4.5\pm0.3^{a}$
Syrphidae	Eristalinus sp. (3)	$39.7 \pm 10.2^{abcd}$	$9.7 \pm 0.7^{abc}$	$6.3\pm0.3^{ab}$
Syrphidae	Episerphus trisectus (4)	$32.3 \pm 7.1^{abcd}$	$5.5 \pm 1.2^{abc}$	$5.8\pm0.5^{ab}$
Syrphidae	Allograpta sp. (5)	$19.4 \pm 4.8^{abcd}$	$3.6 \pm 1.0^{\text{abc}}$	$4.4\pm0.4^{\rm a}$
Calliphoridae	Chrysomya megacephala (4)	$18.0 \pm 8.5^{abcd}$	$7.8 \pm 5.2^{abc}$	$3.6\pm0.5^{a}$
Calliphoridae	Chrysomya chloropyga (7)	$15.0\pm3.5^{\text{abc}}$	$3.4 \pm 1.1^{ab}$	$5.6 \pm 1.3^{ab}$
Vespidae	Polistes sp. (5)	$7.6 \pm 2.5^{ab}$	$1.6 \pm 1.4^{a}$	$4.4 \pm 1.1^{a}$
Vespidae	Belonogaster juncea (3)	$6.0 \pm 2.1$ <sup>ab</sup>	$4.0 \pm 3.5^{abc}$	$3.3\pm0.3^{\rm a}$
Vespidae	Belonogaster griseus (3)	$3.3 \pm 2.4^{a}$	$1.0\pm0.6^{a}$	$4.0 \pm 1.4^{ab}$

Note: N = the total number of individuals of each species that was evaluated. The values are means  $\pm$  SE. Means with a different superscript letter within a column are significantly different (p < 0.05) according to Tukey test.

visitors of a given plant species are efficient pollinators since some could be nectar or pollen robbers and thieves or there could be a mismatch of the morphological trait (body size) with flower size (Rivest & Forrest, 2020). A recent global meta-analysis on avocado pollinators by Dymond et al. (2021) indicated that pollination efficiency of different avocado flower visitors has rarely been documented. Our study is the first to report the pollination efficiency of avocado flower visitors in sub-Saharan Africa.

In terms of frequency and abundance, the contribution of A. *mellifera* to pollination was much higher than other taxa in our study sites. Our results concur with previous studies, that A. *mellifera* is an important avocado pollinator due to its high flower visitation frequency and



**FIGURE 2** Linear regression showing the relationship between (a) pollen on the stigma and pollen on insect, (b) pollen on the insect and flower handling time, and (c) pollen deposited on the stigma and flower handling time. The *R* and *p*-values are indicated on the graph.

abundance (Ish-Am, 2005; Wysoki et al., 2002). The findings by Read et al. (2017) in New Zealand reported that Western honey bees were the dominant flower visitors (92.9%) in all avocado orchards surveyed. Evans et al. (2011) studied the role of insect pollinators in avocado in New Zealand and reported that 97.4% of all flower visitors were honey bees, while in Australia, 37.9% were honey bees. In New Zealand and Australia, A. mellifera is exclusively managed and this might explain the high abundances. In our study, honey bees were the most active flower visitors since they visited avocado flowers between 9:00 AM and 5:00 PM, with the peak time being 11:00 AM. The high numbers recorded for this species could be due to their large social colonies and efficient foraging behaviour that could outcompete solitary bees and other insects (Balfour et al., 2015). In East Africa, the populations of honey bees are essentially wild (Crane, 1999; Mbae, 1999; Mcmenamin et al., 2017). Nevertheless, in Kenya, there are about 2 million hives (Kiingwa et al., 2020), such that most visiting honeybees likely originate from managed colonies. However, previous studies revealed that A. mellifera can abandon avocado flowers when there are alternative blooms in the vicinity (Afik et al., 2006, 2014). Our result showed that flies were also regular avocado flower visitors with an overall abundance of 11% hover flies (Syrphidae) and 16% of 'other flies'. Similar findings of relative abundance of 12% hover flies have been reported in avocado by Dymond et al. (2021), a global review. Also, a study conducted by Evans et al. (2011) reported that 49.7% of the visitors were hover flies, and 12.4% of the visits were from other insects (flies other than hover flies and native bees) for Australia. The result of the present study also shows that the contribution of wasps, especially Polistes sp., was low because of their lower numbers.

Wild and managed pollinators can be essential to supplement honey bees when other flowers are in bloom at the same time in order to reach substantial pollination services. Previous studies highlighted the importance of conserving wild pollinators at the landscape scale (Requier et al., 2019). Therefore, maintaining heterogeneous natural habitats can be an excellent strategy to conserve the abundance of wild pollinators around the orchards (Klein et al., 2012; Potts et al., 2016; Woodcock et al., 2019), which can contribute to avocado production. In addition, other factors such as low genetic variability within an orchard, resource limitations and agronomic practices such as soil properties, fertilization regimes, irrigation, pruning and weeding that might influence the final yield outcomes (Samnegård et al., 2019) have been shown to affect avocado quality and yield.

Our results suggest that A. mellifera and P. incisa are efficient pollinators of avocado after a single visit. This was evident because they showed many pollen grains on their body and had higher pollen deposition onto the stigma compared to other species. The higher the number of pollen grains deposited onto the stigma, the higher the chance of pollination success (Alcaraz & Hormaza, 2021). A study conducted by Ish-Am (2005) in three different avocado varieties (Hass, Ettinger and Reed) in Israel indicated that 20 or more pollen grains are required to reach the stigma for adequate fertilization to take place. It has been shown that pollen deposited during a single visit is a more direct and practical method in assessing pollination efficiency compared to other parameters such as visitor abundance, number of stigma contacts, feeding type or visit duration (King et al., 2013). This study agrees with previous findings by Vithanage (1990) in New South Wales, which indicated that A. mellifera played a leading role in pollen transfer for avocado. Similar findings have also been reported by Wysoki et al. (2002) and Peña (2003) where they found A. mellifera as the primary avocado pollinator, even though Bombus terrestris L. has been reported as an efficient avocado pollinator in Southeast Spain and Israel (Ish-Am & Eisikowitch, 1993; Wysoki et al., 2002). Therefore, A. mellifera and P. incisa can achieve adequate fertilization with an SVD; hence, they are supposed to be efficient avocado flower pollinators.

The high efficiency of A. *mellifera* and *P. incisa* in pollination might be explained by the hairiness of their bodies and their large sizes, which result in more contact with the stigma. Hairiness is considered an essential trait in pollinators as it is involved in pollen collection and transfer (Amador et al., 2017; Roquer-Beni et al., 2020; Thorp, 2000). A study conducted by Stavert et al. (2016) demonstrated that pollinator hairiness is strongly linked to pollination. Furthermore, recent studies have found a positive relationship between body size and amount of pollen deposited per visit in oilseed rape *Brassica napus* L. (Phillips et al., 2018) and watermelon Citrullus lanatus T. (Bartomeus) et al., 2018). With greater body size, pollinators such as A. mellifera and *P. incisa* can carry larger pollen loads and deposit more pollen (Goulnik et al., 2020). In our study, wasps were less important pollinators, perhaps because of a body integument with low pollen adhesion capacity limiting their potential as avocado pollinators (De Vega et al., 2014). This is contrary to some studies that have reported wasps as efficient pollinators (Ish-am et al., 1999; Pérez-Balam et al., 2012). In our study site, Belonogaster griseus was found to transfer more heterospecific pollen than other species, indicating that they visited other flowers in the vicinity than avocado. This might reduce their efficiency as avocado pollinators. Heterospecific pollen transfer occurs in nature and does not result in fruit production due to incompatibility mechanism (morphologically or genetically/phytochemically) and it can lead to unsuccessful fertilization by clogging the stigma; hence, conspecific pollen grains cannot germinate and grow through the stigma into the style and ovary (Mitchell et al., 2009; Morales & Traveset, 2008).

Our result showed a significant difference among the flower insect visitors in terms of flower handling time. The longest flower handling time was recorded in *B. faveata*, followed by *A. mellifera*. Engel and Irwin (2003) indicated that the time spent in the flower might affect floral resource exploitation and consequently the pollination of a given plant species. This is in line with our study, where we found a moderate positive correlation between flower handling time and pollen on the insect body and pollen deposited, indicating that time spent on the flower may play a role in pollination efficiency.

# 5 | CONCLUSION

In our study site in Kenya, this study provides important insights into the pollination efficiency of avocado. We observed that flower-visiting species had different capabilities in transferring compatible pollen grains in avocado, demonstrating the importance of species behaviour and morphological traits in determining pollination efficiency. We had earlier demonstrated the importance of insect pollination in comparison to self-pollination especially in enhancing fruit set and retention (Sagwe et al., 2021). To achieve optimum pollination services for avocado, managed honey bees or conservation habitats of wild living colonies can be valuable tools for growers in improving the yield for avocado, which can help to supplement wild pollinator species. This study is important for developing guidelines for farmers to implement within and around the orchards to support the pollinator species and their corresponding pollination services. For instance, sowing of wildflowers can be a good strategy for increasing diversification of pollination sources for wild pollinators such as hover flies and minimizing the use of harmful chemicals such as pesticides and herbicides. Understanding the efficiency of different pollinators that visit avocado flowers will help determine which species are important to its production. The contribution of genetic variety within an orchard, resource limitations and agronomic practices such as soil properties, fertilization regimes, irrigation, pruning and weeding that might influence the final yield outcomes needs to be investigated.

### AUTHOR CONTRIBUTIONS

H. Michael G. Lattorff, Thomas Dubois and Rose Nyakemiso Sagwe conceived the ideas and designed methodology. Rose Nyakemiso Sagwe collected the data. Rose Nyakemiso Sagwe, Marcell K. Peters and Ingolf Steffan-Dewenter analysed the data. Rose Nyakemiso Sagwe, Marcell K. Peters and H. Michael G. Lattorff led the writing of the manuscript. All authors discussed the results and contributed critically to the drafts and gave final approval for publication.

### ACKNOWLEDGEMENTS

This work received financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned and administered through the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Fund for International Agricultural Research (FIA), grant number 17.7860.4-001; UK's Foreign, Commonwealth & Development Office (FCDO); the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC); the Federal Democratic Republic of Ethiopia; and the Government of the Republic of Kenya. The views expressed herein do not necessarily reflect the official opinion of the donors. R.N.S. was supported by the Dissertation Research Internship Programme (DRIP) at icipe under a PhD scholarship. We thank Dr. Robert Copeland from icipe and Josiah from NMK for help in identifying insect specimens; Robert Munyao in assisting laboratory work; and Tabitha Magero, Ephantus Kimani, Sheila Koech and Geoffrey Entabo for support during field data collection. This work would have been impossible without the co-operation of avocado farmers.

#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

Data are available from the Dryad Digital Repository: https://doi.org/ 10.5061/dryad.dbrv15f48.

# ORCID

Rose Nyakemiso Sagwe https://orcid.org/0000-0001-7488-429X Marcell K. Peters https://orcid.org/0000-0002-1262-0827 H. Michael G. Lattorff https://orcid.org/0000-0002-8603-6332

### PEER REVIEW

The peer review history for this article is available at: https://publons. com/publon/10.1002/2688-8319.12178 (Sagwe et al., 2022).

### REFERENCES

- Afik, O., Dag, A., Kerem, Z., & Shafir, S. (2006). Analyses of avocado (Persea americana) nectar properties and their perception by honey bees (Apis mellifera). Journal of Chemical Ecology, 32(9), 1949–1963. https://doi.org/ 10.1007/s10886-006-9120-1
- Afik, O., Delaplane, K. S., Shafir, S., Moo-Valle, H., & Quezada-Euán, J. J. G. (2014). Nectar minerals as regulators of flower visitation in stingless bees and nectar hoarding wasps. *Journal of Chemical Ecology*, 40(5), 476–483. https://doi.org/10.1007/s10886-014-0455-8

- Alcaraz, M. L., & Hormaza, J. I. (2009). Avocado pollination and fruit set a perspective from Spain. *California Avocado Society Yearbook*, *California*, 92, 113–135.
- Alcaraz, M. L., & Hormaza, J. I. (2021). Fruit set in Avocado: Pollen limitation, pollen load size, and selective fruit abortion. *Journal of Agronomy*, 11(8), 1603. https://doi.org/10.3390/agronomy11081603
- Amador, G. J., Matherne, M., Waller, D., Mathews, M., Gorb, S. N., & Hu, D. L. (2017). Honey bee hairs and pollenkitt are essential for pollen capture and removal. *Bioinspiration and Biomimetics*, 12(2), 026015. https://doi. org/10.1088/1748-3190/aa5c6e
- Amare, M., Mariara, J., Oostendorp, R., & Pradhan, M. (2019). The impact of smallholder farmers' participation in avocado export markets on the labor market, farm yields, sales prices, and incomes in Kenya. *Land Use Policy*, 88, 104168. https://doi.org/10.1016/j.landusepol.2019.104168
- Balfour, N. J., Gandy, S., & Ratnieks, F. L. W. (2015). Exploitative competition alters bee foraging and flower choice. *Journal of Behavioral Ecology and Sociobiology*, 69(10), 1731–1738. https://doi.org/10.1007/s00265-015-1985-y
- Bartomeus, I., Cariveau, D. P., Harrison, T., & Winfree, R. (2018). On the inconsistency of pollinator species traits for predicting either response to land-use change or functional contribution. *Oikos*, 127(2), 306–315.
- Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1– 48. https://doi.org/10.18637/jss.v067.i01
- Beattie, A. J. (1971). A technique for the study of insect-borne pollen. *The Pan-Pacific Entomologist*, 47(1), 82.
- Bergamo, P. J., Rech, A. R., Brito, V. L., & Sazima, M. (2016). Flower colour and visitation rates of *Costus arabicus* support the 'bee avoidance' hypothesis for red-reflecting hummingbird-pollinated flowers. *Functional Ecology*, 30(5), 710–720.
- Burkle, L. A., & Alarcón, R. (2011). The future of plant-pollinator diversity: Understanding interaction networks across time, space, and global change. American Journal of Botany, 98(3), 528–538. https://doi.org/10. 3732/ajb.1000391
- Crane, E. (1999). The world history of beekeeping and honey hunting. Routledge.
- Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bommarco, R., Carvalheiro, L. G., Chaplin-kramer, R., Garibaldi, L. A., Ghazoul, J., Grab, H., Jonsson, M., Daniel, S., Andersson, G. K. S., Badenhausser, I., Baensch, S., Ekroos, J., Fijen, T., Franck, P., Freitas, B. M., ... Björn, K. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, 5(10), 1–19.
- De Vega, C., Herrera, C. M., & Dötterl, S. (2014). Floral volatiles play a key role in specialized ant pollination. *Perspectives in Plant Ecology, Evolution* and Systematics, 16(1), 32–42.
- Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., Basu, P., Buchori, D., Galetto, L., Garibaldi, L. A., Gemmill-Herren, B., Howlett, B. G., Imperatriz-Fonseca, V. L., Johnson, S. D., Kovács-Hostyánszki, A., Kwon, Y. J., Lattorff, H. M. G., Lungharwo, T., Seymour, C. L., ... Potts, S. G. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature Ecology & Evolution*, 5(10), 1453–1461. https://doi.org/10.1038/s41559-021-01534-9
- Dymond, K., Celis-Diez, J. L., Potts, S. G., Howlett, B. G., Willcox, B. K., & Garratt, M. P. D. (2021). The role of insect pollinators in avocado production: A global review. *Journal of Applied Entomology*, 145(5), 369–383. https://doi.org/10.1111/jen.12869
- Engel, E. C., & Irwin, R. E. (2003). Linking pollinator visitation rate and pollen receipt. American Journal of Botany, 90(11), 1612–1618. https://doi.org/ 10.3732/ajb.90.11.1612
- Evans, L. J., Goodwin, R. M., & Howlett, B. G. (2011). The role of insect pollinators in avocado (Persea americana) pollination in New Zealand and Australia. Proceedings VII World Avocado Congress (5–9 September) pp. 7 Cairns, Australia.
- Fishbein, M., & Venable, D. L. (1996). Diversity and temporal change in the effective pollinators of Asclepias tuberosa. Ecology, 77(4), 1061–1073.

- Fumero-Cabán, J. J., & Meléndez-Ackerman, E. J. (2007). Relative pollination effectiveness of floral visitors of *Pitcairnia angustifolia* (Bromeliaceae). *American Journal of Botany*, 94(3), 419–424.
- Garibaldi, L. A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., Kremen, C., Carvalheiro, L. G., Harder, L. D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N. P., Dudenhöffer, J. H., Freitas, B. M., Ghazoul, J., Greenleaf, S., ... Klein, A. M. (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, 339(6127), 1608–1611.
- Garibaldi, L. A., Carvalheiro, L. G., Leonhardt, S. D., Aizen, M. A., Blaauw, B. R., Isaacs, R., Kuhlmann, M., Kleijn, D., Klein, A. M., Kremen, C., Morandin, L., Scheper, J., & Winfree, R. (2014). From research to action: Enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment*, 12(8), 439–447. https://doi.org/10.1890/130330
- Goulnik, J., Plantureux, S., Van Reeth, C., Baude, M., Mesbahi, G., & Michelot-Antalik, A. (2020). Facial area and hairiness of pollinators visiting seminatural grassland wild plants predict their facial pollen load. *Ecological Entomology*, 45(6), 1296–1306.
- Graves, S., Piepho, H. P., & Selzer, M. L. (2015). 'multcompView: Visualizations of paired comparisons. R package.
- Greenleaf, S. S., & Kremen, C. (2006). Wild bees enhance honey bees' pollination of hybrid sunflower. Proceedings of the National Academy of Sciences of the United States of America, 103(37), 13890–13895.
- Huda, A. N., Salmah, M. R., Hassan, A. A., Hamdan, A., & Razak, M. N. (2015). Pollination services of mango flower pollinators. *Journal of Insect Science*, 15(1), 113.
- HCDA. (2017). Horticultural crops directorate validated report 2016–2017. Agriculture And Food Authority (AFA).
- Ish-Am, G., & Eisikowitch, D. (1993). The behaviour of honey bees (Apis mellifera) visiting avocado (Persea americana) flowers and their contribution to its pollination. Journal of Apicultural Research, 32(3–4), 175–186.
- Ish-Am, G., & Eisikowitch, D. (1998). Low attractiveness of avocado (Persea americana Mill.) flowers to honeybees (Apis mellifera L.) limits fruit set in Israel. The Journal of Horticultural Science and Biotechnology, 73(2), 195– 204.
- Ish-am, G., Barrientos-Priego, F., Castaneda-Vildozola, A., & Gazit, S. (1999). Avocado (Persea americana Mill.) pollinators in its region of origin. Revista Chapingo Serie Horticultura, 5, 137–143.
- Ish-Am, G. (2005). Avocado pollination: A review. New Zealand and Australia Avocado Growers' Conference, Tauranga New Zealand, 2005.
- Ish-Am, G., & Lahav, E. (2011). Evidence for a major role of honeybees (Apis mellifera) rather than wind during avocado (Persea americana Mill.) pollination. The Journal of Horticultural Science and Biotechnology, 86(6), 589–594. https://doi.org/10.1080/14620316.2011.11512808
- Jauker, F., Bondarenko, B., Becker, H. C., & Steffan-Dewenter, I. (2012). Pollination efficiency of wild bees and hoverflies provided to oilseed rape. *Agricultural and Forest Entomology*, 14, 81–87.
- Kiingwa, K. M., Philomena, M., & Joseph, M. (2020). Determinants of modern box hives adoption in Kitui County, Kenya. International Journal Education and Research, 8(10), 121–132.
- King, C., Ballantyne, G., & Willmer, P. G. (2013). Why flower visitation is a poor proxy for pollination: Measuring single-visit pollen deposition, with implications for pollination networks and conservation. *Methods in Ecology and Evolution*, 4(9), 811–818. https://doi.org/10.1111/2041-210X. 12074
- Klein, A. M., Brittain, C., Hendrix, S. D., Thorp, R., Williams, N., & Kremen, C. (2012). Wild pollination services to California almond rely on seminatural habitat. *Journal of Applied Ecology*, 49(3), 723–732.
- Klein, A.-M., Steffan-Dewenter, I., & Tscharntke, T. (2003). Fruit set of highland coffee increases with the diversity of pollinating bees. Proceedings of the Royal Society of London B: Biological Sciences, 270, 955–961.
- Krause, G. L., & Wilson, W. T. (1981). Honey bee pollination and visitation patterns on hybrid oilseed sunflowers in central Wyoming (Hymenoptera: Apidae). *Journal of the Kansas Entomological Society*, 54(1), 75–82.

- Lenth, R. V. (2016). Least-squares means: The R package Ismeans. Journal of Statistical Software, 69(1), 1–33. https://doi.org/10.18637/jss.v069.i01
- Lye, G. C., Jennings, S. N., Osborne, J. L., & Goulson, D. (2011). Impacts of the use of nonnative commercial bumble bees for pollinator supplementation in raspberry. *Journal of Economic Entomology*, 104(1), 107–114. https://doi.org/10.1603/EC10092
- Mitchell, R. J., Flanagan, R. J., Brown, B. J., Waser, N. M., & Karron, J. D. (2009). New frontiers in competition for pollination. *Annals of Botany*, 103(9), 1403–1413.
- Morales, C. L., & Traveset, A. (2008). Interspecific pollen transfer: Magnitude, prevalence and consequences for plant fitness. *Critical Reviews in Plant Sciences*, 27(4), 221–238.
- Mbae, R. M. (1999). Overview of beekeeping development in Kenya. Proceedings, First International Workshop: The Conservation and Utilization of Commercial Insects, pp. 103–105.
- McMenamin, A., Mumoki, F., Frazier, M., Kilonzo, J., Mweu, B., Baumgarten, T., Patch, H., Torto, B., Masiga, D., Tumlinson, J., Grozinger, C., & Muli, E. (2017). The impact of hive type on the behavior and health of honey bee colonies (*Apis mellifera*) in Kenya. *Apidologie*, 48(5), 703–715.
- Ne'eman, G., Jürgens, A., Newstrom-Lloyd, L., Potts, S. G., & Dafni, A. (2010). A framework for comparing pollinator performance: Effectiveness and efficiency. *Biological Reviews*, 85(3), 435–451. https://doi.org/10.1111/j. 1469-185X.2009.00108.x
- Peña, J. E. (2003). Insectos polinizadores de frutales tropicales: No solo las abejas llevan la miel al panal. Manejo Integrado de Plagas y Agroecología (Costa Rica), 69, 6–20.
- Pérez-Balam, J., Quezada-Euán, J. J. G., Alfaro-Bates, R., Medina, S., McKendrick, L., Soro, A., & Paxton, R. J. (2012). The contribution of honey bees, flies and wasps to avocado (*Persea americana*) pollination in southern Mexico. *Journal of Pollination Ecology*, *8*, 42–47.
- Potts, S. G., Roberts, S. P. M., Dean, R., Marris, G., Brown, M. A., Jones, R., Neumann, P., & Settele, J. (2010). Declines of managed honey bees and beekeepers in Europe. *Journal of Apicultural Research*, 49(1), 15–22. https://doi.org/10.3896/IBRA.1.49.1.02
- Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. J. (2016). Safeguarding pollinators and their values to human well-being. *Nature*, 540(7632), 220–229.
- Phillips, B. B., Williams, A., Osborne, J. L., & Shaw, R. F. (2018). Shared traits make flies and bees effective pollinators of oilseed rape (*Brassica napus* L.). *Journal of Basic and Applied Ecology*, 32(2017), 66–76. https://doi.org/ 10.1016/j.baae.2018.06.004
- Read, S. F. J., Howlett, B. G., Jesson, L. K., & Pattemore, D. E. (2017). Insect visitors to avocado flowers in the Bay of Plenty, New Zealand. New Zealand Plant Protection, 70, 38–44.
- Rader, R., Bartomeus, I., Garibaldi, L. A., Garratt, M. P. D., Howlett, B. G., Winfree, R., Cunningham, S. A., Mayfield, M. M., Arthur, A. D., Andersson, G. K. S., Bommarco, R., Brittain, C., Carvalheiro, L. G., Chacoff, N. P., Entling, M. H., Foully, B., Freitas, B. M., Gemmill-Herren, B., Ghazoul, J., ... Woyciechowski, M. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences of the United States of America*, 113(1), 146–151. https://doi.org/10.1073/ pnas.1517092112
- Requier, F., Garnery, L., Kohl, P. L., Njovu, H. K., Pirk, C. W., Crewe, R. M., & Steffan-Dewenter, I. (2019). The conservation of native honey bees is crucial. *Trends in Ecology & Evolution*, 34(9), 789–798.
- Roquer-Beni, L., Rodrigo, A., Arnan, X., Klein, A. M., Fornoff, F., Boreux, V., & Bosch, J. (2020). A novel method to measure hairiness in bees and other insect pollinators. *Journal of Ecology and Evolution*, 10(6), 2979–2990. https://doi.org/10.1016/j.tree.2019.04.008
- Rivest, S., & Forrest, J. R. K. (2020). Defence compounds in pollen: Why do they occur and how do they affect the ecology and evolution of bees? *New Phytologist*, 225(3), 1053–1064. https://doi.org/10.1111/nph. 16230
- Sagwe, R. N., Peters, M. K., Dubois, T., Steffan-Dewenter, I., & Lattorff, H. M. G. (2021). Pollinator supplementation mitigates pollination deficits

in smallholder avocado (*Persea americana* Mill.) production systems in Kenya. *Basic and Applied Ecology*, *56*, 392–400.

- Sagwe, R., Peters, M., Dubois, T., Steffan-Dewenter, I., & Lattorff, M. (2022). Pollinator efficiency of avocado (Persea americana) flower insect visitors. Dryad digital repository, https://doi.org/10.5061/dryad.dbrv15f48
- Samnegård, U., Hambäck, P. A., & Smith, H. G. (2019). Pollination treatment affects fruit set and modifies marketable and storable fruit quality of commercial apples. *Royal Society Open Science*, 6(12), 190326. https://doi. org/10.1098/rsos.190326
- Stavert, J. R., Liñán-Cembrano, G., Beggs, J. R., Howlett, B. G., Pattemore, D. E., & Bartomeus, I. (2016). Hairiness: The missing link between pollinators and pollination. *PeerJ*, 4, e2779.
- Thapa, R. B. (2006). Honeybees and other insect pollinators of cultivated plants: A review. Journal of the Institute of Agriculture and Animal Science, 27, 1–23.
- Thorp, R. W. (2000). The collection of pollen by bees. In A. Dafni, M. Hesse, & E. Pacini (Eds.), *Pollen and pollination* (pp. 211–223). Springer.
- Visscher, P. K., & Seeley, T. D. (1982). Foraging strategy of honeybee colonies in a temperate deciduous forest. *Ecology*, 63(6), 1790–1801.
- Vithanage, V. (1990). The role of the European honeybee (Apis mellifera L.) in avocado pollination. Journal of Horticultural Science, 65(1), 81–86. https:// doi.org/10.1080/00221589.1990.11516033
- Winfree, R., Williams, N. M., Dushoff, J., & Kremen, C. (2007). Native bees provide insurance against ongoing honey bee losses. *Ecology Letters*, 10(11), 1105–1113.
- Woodcock, B. A., Garratt, M. P. D., Powney, G. D., Shaw, R. F., Osborne, J. L., Soroka, J., Lindström, S. A. M., Stanley, D., Ouvrard, P., Edwards, M. E., Jauker, F., McCracken, M. E., Zou, Y., Potts, S. G., Rundlöf, M., Noriega, J. A., Greenop, A., Smith, H. G., Bommarco, R., ... Pywell, R. F. (2019). Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. *Nature Communications*, 10(1), 1–10. https://doi.org/10.1038/s41467-019-09393-6
- Wysoki, M., Van Den Berg, M. A., Ish-Am, G., Gazit, S., Peña, J. E., & Waite, G. K. (2002). Pests and pollinators of avocado. In J. E. Pena, J. L. Sharp, & M. Wysoki (Eds.), Tropical fruit pests and pollinators: Biology, economic importance, natural enemies and control (pp. 223–293). CABI.
- Zou, Y., Bianchi, F. J., Jauker, F., Xiao, H., Chen, J., Cresswell, J., Luo, S., Huang, J., Deng, X., Hou, L., & van der Werf, W. (2017). Landscape effects on pollinator communities and pollination services in small-holder agroecosystems. Agriculture, Ecosystems & Environment, 246, 109–116.

### SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Fig. S1**. Visitation frequency of the most abundant insect groups during the avocado blooming period in Murang'a county, Kenya.

**Fig. S2**. Avocado pollen grains with and without stain taken under a microscope at 100× magnification. (a) General view of pollen grains with stain and (b) pollen without stain.

supplementary material Table S1. Percentage of heterospecific pollen on the insect and heterospecific pollen deposited on the stigma of avocado flowers across smallholder avocado farms in Murang'a County, Kenya.

How to cite this article: Sagwe, R. N., Peters, M. K., Dubois, T., Steffan-Dewenter, I., & Lattorff, H. M. G. (2022). Pollinator efficiency of avocado (*Persea americana*) flower insect visitors. *Ecological Solutions and Evidence*, *3*, e12178. https://doi.org/10.1002/2688-8319.12178