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ENHANCING TOMATO FRUIT SET IN OPEN FIELDS THROUGH POLLINATION SERVICE BY BUZZING BEES *Xylocopa* spp.

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ABSTRACT

Pollination is a vital process for the reproduction of flowering plants and significantly influences agricultural yields. Pollination efficiency directly affects fruit set and quality in tomato *Solanum lycopersicum* cultivation. This study explored the role of *Xylocopa* spp., or buzzing bees, in enhancing tomato pollination in open-field conditions, where traditional pollinators, such as honeybees, may be less effective. Using randomized block design experiments, the effects of *Xylocopa* pollination on fruit set, size, and seed development were compared to those of treatments involving other pollinators or their exclusion. The findings indicated that *Xylocopa* bees had significantly increased fruit set, with improved fruit size and higher seed counts. These results highlight the superiority of vibrational buzz pollination performed by *Xylocopa* spp., which efficiently releases pollen from the anthers. Additionally, *Xylocopa*-pollinated tomatoes demonstrated enhanced resilience to environmental stressors, underscoring their potential role in sustainable agriculture. The study concluded that integrating *Xylocopa* spp. into open-field tomato cultivation can optimize pollination services, leading to higher yields and better-quality fruit. These findings advocate for the conservation and promotion of *Xylocopa* populations to support eco-friendly and efficient agricultural practices. Further research on their ecological dynamics and interactions with other pollinators is recommended to fully harness their benefits in agroecosystems.

Keywords: Buzz pollination; fruit set enhancement; tomato pollination; sustainable agriculture; X*ylocopa* bees

ABSTRAK

Pendebungaan merupakan proses penting untuk pembiakan tumbuhan berbunga dan memberi pengaruh yang ketara terhadap hasil pertanian. Kecekapan pendebungaan secara langsung mempengaruhi pembentukan buah dan kualitinya dalam penanaman tomato (*Solanum lycopersicum*). Kajian ini meneliti peranan *Xylocopa* spp., atau lebah penggetar, dalam meningkatkan pendebungaan tomato di ladang terbuka, di mana pendebunga tradisional seperti lebah madu mungkin kurang berkesan. Menggunakan reka bentuk blok rawak, kesan pendebungaan oleh *Xylocopa* terhadap pembentukan buah, saiz buah, dan pembangunan biji telah dibandingkan dengan rawatan yang melibatkan pendebunga lain atau pengecualian pendebungaan. Hasil kajian menunjukkan bahawa lebah *Xylocopa* meningkatkan secara signifikan pembentukan buah, dengan saiz buah yang lebih besar dan jumlah biji yang lebih tinggi. Penemuan ini menekankan kelebihan pendebungaan bergetar yang dilakukan oleh *Xylocopa* spp., yang cekap dalam melepaskan debunga daripada benang sari. Selain itu, tomato yang dibuahi oleh *Xylocopa* menunjukkan daya tahan yang lebih baik terhadap tekanan persekitaran, menekankan potensi mereka dalam pertanian lestari. Kajian ini menyimpulkan bahawa integrasi *Xylocopa* spp. dalam penanaman tomato di ladang terbuka dapat mengoptimumkan perkhidmatan pendebungaan, membawa kepada hasil yang lebih tinggi dan buah berkualiti lebih baik. Penemuan ini juga menyokong usaha pemeliharaan dan penggalakan populasi *Xylocopa* bagi menyokong amalan pertanian mesra alam dan efisien. Kajian lanjut mengenai dinamik ekologi mereka dan interaksi dengan pendebunga lain disyorkan untuk memanfaatkan sepenuhnya manfaat mereka dalam agroekosistem.

Kata kunci: Pendebungaan bergetar; peningkatan pembentukan buah; pendebungaan tomato; pertanian lestari; lebah *Xylocopa*

INTRODUCTION

Pollination is an essential process for flowering plants' successful reproduction and also directly affects fruit set and crop yield. Pollination is of paramount importance in tomato *Solanum lycopersicum* as it impacts the quantity and quality of the fruit produced (Wan nur Asiah et al. 2021). Although wind contributes to pollination, most plants rely on insects such as bees, which transfer pollen more effectively and in a targeted manner than wind. Although many bee species exhibit this life history pattern, only a few, notably species in the genus *Xylocopa*, commonly referred to as the buzzing bees, are effective at pollinating certain crops such as tomatoes through a method called buzz pollination. Buzz pollination is characterized by the bee’s thoracic muscles generating high-frequency vibrations that detach pollen from the flowers’ anthers (Jankauski et al. 2022; Vallejo-Marín 2022). This methodology is particularly effective for plant species whose pollen is not readily dispersed through gravitational forces or simple physical contact, but requires vibrational energy, such as in the case of tomato flowers. Previous studies have demonstrated that *Xylocopa* bees exhibit superior efficiency in pollen transfer compared to other bee species, such as *Apis mellifera*, which lack the capacity to perform buzz pollination (Mesquita-Neto et al. 2021; Tayal & Kariyat 2021).

In recent years, there has been increasing scholarly interest in elucidating the specific role of *Xylocopa* in pollination within open-field agricultural environments. While numerous studies have substantiated that *Xylocopa* bees enhance fruit set and crop yields in various agricultural systems, the impact of these bees on tomato pollination in open fields has been less extensively investigated. A recent study by Vallejo-Marín and Russell (2024) demonstrated that *Xylocopa* bees significantly enhanced tomato fruit set in open-field environments, particularly when *Apis mellifera* populations were diminished. The researchers' findings indicate that the vibrational pollination performed by *Xylocopa* not only augments the quantity of fruit produced but also enhances fruit quality with respect to size and uniformity. Further, research by Keasar (2010) highlighted the crucial role of solitary bees like *Xylocopa* in open-field tomato cultivation. *Xylocopa* species were particularly effective in pollinating larger tomato varieties that require more specialized pollination. In contrast to *A. mellifera*, which predominantly focuses on smaller floral structures, *Xylocopa* bees were observed to facilitate the transfer of greater pollen quantities, thereby promoting improved fruit set and increased tomato size. Furthermore, while *Xylocopa* was the primary pollinator, the presence of other bee species, such as honeybees and stingless bees, further augmented pollination efficiency. However, the researchers concluded that optimal pollination and fruit set were achieved when *Xylocopa* populations were abundant, underscoring the necessity to protect and conserve this species for sustainable agricultural practices (Santos et al. 2014; Toni et al. 2021).

Despite the growing body of evidence supporting the role of *Xylocopa* in tomato pollination, significant knowledge gaps persist in our understanding of how these bees contribute to fruit set specifically under open-field conditions. While numerous studies have focused on controlled environments or other crops, further investigation is necessary to fully elucidate the contribution of *Xylocopa* spp. to tomato production in real-world agricultural settings. This research aims to address this knowledge gap by examining the visitation behavior, pollination efficiency, and overall impact of *Xylocopa* spp. on tomato fruit set in open-field cultivation. The findings will clarify the role of *Xylocopa* as a key pollinator in sustainable tomato farming.

MATERIALS AND METHODS

Study Area

The study was conducted in an open-field tomato cultivation site located in Herlang Subdistrict, Bulukumba Regency, South Sulawesi (5°22'37.0"S 120°23'36.7"E) (Figure 1). The chosen site provided typical agricultural conditions with minimal intervention from managed pollinators such as honeybees.

Figure 1. Sampling and observation locations for pollination services by *Xylocopa* spp

Experimental Materials and Field Setup

Healthy tomato plants (*Lycopersicon esculentum*) cultivated in open-field plots under typical agricultural conditions in Bulukumba Regency, South Sulawesi, Indonesia. The selected tomato cultivar is commonly grown by local farmers and is known for its reliance on effective insect pollination for optimal fruit development. For pollination experiments, artificial nesting boxes (18 x 18 x 20 cm) made from untreated wood were prepared to attract and support populations of *Xylocopa* spp. These boxes were designed to mimic the bees' natural nesting preferences and were installed near tomato plots assigned for *Xylocopa* introduction. Bees were captured using wooden-tube traps baited with floral scent and then released near nesting boxes after identification to ensure active pollination.

To support data collection, various measurement tools were employed. A digital caliper (±0.01 mm accuracy) was used to determine fruit diameter, while a precision electronic scale (±0.01 g) was used to weigh individual fruits. For seed analysis, dissecting tools and magnifying lenses were used to count and assess seed development. Field notebooks and standardized observation sheets were used to record bee visitation behaviors, and environmental data were monitored using a portable weather station equipped with sensors for temperature, humidity, and wind speed.

Insect netting was used in exclusion treatments to prevent access by specific pollinators, particularly *Xylocopa* spp., without altering other environmental conditions. Supporting structures such as wooden stakes and mesh screens were also employed to define treatment plots and to support netting installations. All equipment and materials used were selected to minimize ecological disturbance and were suitable for prolonged use in outdoor agricultural environments.

Field Set-up and Sampling Design

The tomato plants were cultivated in rows in an area of approximately 0.5 hectares. The climate in this region is characterized by a tropical monsoon climate with an average temperature of 26–32°C, annual rainfall of 1,500–2,000 mm, and relative humidity ranging from 70% to 85%, which are representative of the growing conditions in many tomato farming areas. This open-field setting is essential to investigate the role of *Xylocopa* spp. bees and other pollinators in natural tomato pollination processes, as it reflects the conditions under which most commercial tomato crops are grown.

The study employed a randomized block design (RBD) to assess how various pollinator species affect tomato fruit set and quality (Ariel & Farrington 2010). The experimental field was divided into multiple plots, each assigned a different pollination treatment to study the impact of *Xylocopa* spp. and other pollinators on tomato yield. In control plots, all pollinators were allowed access, enabling natural pollination. This design allowed researchers to observe tomato plant performance under typical open-field pollination conditions, with a variety of pollinators contributing to the process, including managed *A. mellifera* and wild bees like *Xylocopa*.

In the second treatment group, *Xylocopa* spp. were excluded from the plots using physical barriers like insect netting. This exclusion aimed to study the effects on tomato fruit set and quality when *Xylocopa* spp. were absent, while other pollinators, such as *A. mellifera* and native bees, could still pollinate. The third treatment involved introducing *Xylocopa* spp. bees by placing artificial bee nesting boxes near the tomato plants to attract and sustain *Xylocopa* populations. Temporary trapping methods ensured the continuous presence of these bees for research on their role in pollination and fruit production. The fourth treatment allowed unrestricted access to natural pollinators, including *Xylocopa* spp., honeybees, and stingless bees. This treatment represented typical open-field pollination scenarios with diverse pollinators interacting with the crops. Each treatment was replicated four times in different blocks to minimize spatial variation and ensure statistical reliability. The study lasted three months, covering tomato plant flowering and fruiting stages crucial for assessing the impact of pollination treatments on fruit set and quality.

Bee Behavior Observation

During the peak flowering period, direct observations were carried out to study the visitation behavior of *Xylocopa* spp. on randomly chosen tomato plants in each experimental plot. Observations lasted for 2 hours per day, at multiple times from 9 AM to 11 AM, 12 PM to 2 PM, and 3 PM to 5 PM to capture a comprehensive view of pollinator activity. Various key parameters were recorded to evaluate the visiting behavior of *Xylocopa* spp. This included quantifying the number of *Xylocopa* bees visiting each plant to assess abundance and visit frequency. The average duration of each bee's visit to individual flowers was measured, along with the number of flowers visited per bee within specific time intervals. Special attention was paid to buzzing behavior, where investigators observed how *Xylocopa* bees performed vibrational pollination on the flowers, essential for releasing pollen and facilitating successful pollination in tomatoes. Instances of flower damage by bees or disruptions in the pollination process were carefully documented. Monitoring also included the presence and behavior of other pollinators like *A. mellifera* and stingless bee to understand the overall pollination community and compare their effectiveness in contributing to tomato fruit set.

Pollination Effectiveness

Pollination success was evaluated using three parameters: fruit set, fruit size, and seed development. Fruit set, defined as the ratio of flowers that matured into fruit post-pollination, served as the primary metric. This was quantified by enumerating flowers on each plant at the onset of flowering and subsequently recording the number of fruits that were developed in the study. A total of 240 hours of observation were conducted over 30 days during the flowering period. Fruit quality was also evaluated by focusing on tomato size and mass. After harvest, 20 fruits per plot were randomly selected. A digital caliper was employed to determine the diameter (in millimeters), and a precision scale was used to ascertain the weight (in grams). This approach enabled assessment of the impact of pollination treatments, particularly the influence of *Xylocopa* spp., on the overall dimensions and market viability of tomatoes. These measurements were conducted at the study terminus to ensure full fruit maturation and an accurate representation of the treatment effects. Seed development within the fruit was examined as an additional indicator of pollination efficacy. The seed count per fruit was determined for the sampled tomatoes, along with an assessment of the seed size and development. Only physical seed counts were performed, seed viability was not tested. A greater number of seeds and well-formed seeds typically signifies more effective pollination.

Data Analysis

The data on fruit set and quality were analyzed using Analysis of Variance (ANOVA) to determine whether there were significant differences among the treatment groups (control, *Xylocopa* exclusion, *Xylocopa* introduction, and mixed pollination). Data normality was verified using the Shapiro–Wilk test and homogeneity of variance with Levene's test before conducting ANOVA. Percentage data (fruit set) were arcsine-square-root transformed prior to ANOVA to meet assumptions of normality and homogeneity of variance. Post hoc Tukey's tests were conducted to identify the specific treatments that differed significantly from one another. Regression analysis was performed to assess the relationship between the number of *Xylocopa* visits and fruit set and fruit quality. Linear regression analysis was applied to evaluate the relationship between *Xylocopa* visitation rate and fruit-set parameters. Additionally, a Generalized Linear Model (GLM) was applied to account for other variables that could influence pollination success, such as environmental factors, including temperature, humidity, and wind speed (Antúnez et al. 2017; Jamil et al. 2013; Shrestha et al. 2018; Uthoff & Ruxton 2022). Statistical analyses were performed using IBM SPSS Statistics v26, with a significance level set at *P<0.05*.

Environmental Variables

Environmental variables, including temperature (°C), relative humidity (%), and wind speed (m s^{-1}), were continuously recorded throughout the study period using an on-site automatic weather station (Davis Vantage Pro2, Davis Instruments, USA). The station was equipped with integrated sensors for temperature (accuracy±0.5 °C), humidity (±3%), and wind speed (±0.3 m s^{-1}). Measurements were automatically logged at 15-minute intervals and subsequently averaged to obtain daily means. The weather station was installed within the experimental plot at a height of 2 m above ground level to ensure representative microclimatic conditions. These environmental data were incorporated into the statistical analyses to control for potential effects of temperature, humidity, and wind fluctuations on pollinator activity and flower receptivity.

RESULTS AND DISCUSSION

Bee Visitation Behavior

Observations were conducted over 30 consecutive days, covering the full anthesis period. For that, we recorded their visitation behaviour by quantifying plant visitation within plant per hour slot. In the control plot, *Xylocopa* bees were the principal pollinators, accounting for approximately 60 % of all visits. Mean visitation rate of *Xylocopa* spp. was 5.2 visits (visits per plant per hour) with a surge between 10:00 AM and 2:00 PM during the most active flowering period. Visitation behavior was quantified as the number of visits per plant per hour. Excluding *Xylocopa* spp. significantly reduced visitation rates in the exclusion plots. Honeybees *A. mellifera* were the most frequent pollinator visiting 80% of visits. The average number of visits per plant hour to the exclusion plot was 3.1, and most of those visits occurred during peak visitation hours (7:00 AM – 9:00 AM). This decline in visitation rate and the presence of *Xylocopa* in the unapproval plot, indicates that, under natural conditions, *Xylocopa* bees are likely an important pollinator (Figure 2).

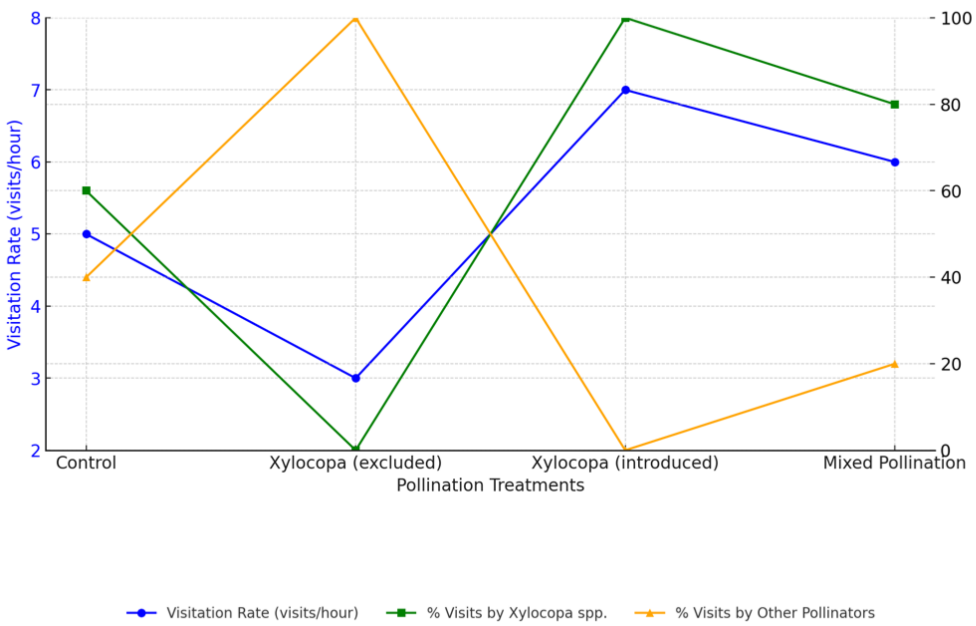

Figure 2. Pollinator visitation rates and proportions across treatments

In the *Xylocopa* spp. Introduction plot, during which all *Xylocopa* bees were actively introduced, visitation rate was greatest at 7.8 visits per plant per hour. In the introduction plots, *Xylocopa* accounted for nearly all visits (>95 %) (each flower visit was made by a tomato flower-specialist). Peak activity was observed for *Xylocopa* between 11:00 AM and 1:00 PM, and average time spent per flower per bee was 20 s when the bees were engaged in vibrational (buzz) pollination. The mixed-pollination plot had a visitation rate of 6.5 visits per plant per hour, with *Xylocopa*, honeybees, and stingless bees contributing 55 %, 30 %, and 15 % of visits, respectively. In this treatment, 55% of visits were by *Xylocopa* bees, 30% by honeybees, and 15% by stingless bees. Peak activity across all species was observed between 09:00 and 15:00, which suggests that multiple species of pollinators contribute to tomato pollination (Table 1).

Table 1. Bee visitation behavior in different pollination treatments

Treatment	Total Visits per Plant per Hour	% of Visits by *Xylocopa* spp.	% of Visits by Other Pollinators	Peak Activity Time
Control	5.2	60%	40%(*Apis* sp. 35%, *Tetragonula* sp. 5%)	10:00 AM–2:00 PM
Xylocopa spp. (Exclusion)	3.1	0%	80% (*Apis* sp.)	7:00 AM 9:00 AM
Xylocopa spp. (Introduction)	7.8	100%	0%	11:00 AM–1:00 PM
Mixed Pollination	6.5	55%	30% (*Apis* sp.), 15%(*Tetragonula* sp.)	9:00 AM–3:00 PM

In this study, *Xylocopa* spp. were identified as the most effectual pollinators, making up 60% of all visits in the control treatment, and 100% of the visits when actively moved. This result corresponds with earlier studies that show *Xylocopa* as one of the most effective pollinators of solanaceous crops such as tomatoes. A study by Cooley and Vallejo-Marín (2021) showed that *Xylocopa* spp. exhibit a significant pollination efficiency in tomato crops due to their unique ability to perform vibrational pollination that increases the efficiency of pollen transfer. Vibrational pollination is especially effective in tomato plants, a flower from which pollen would otherwise generate constraint in referred anthers. Our findings also support previous findings of Keasar (2010),who has shown previously that *Xylocopa tranquebarica* and *Xylocopa virginica* are capable of increasing fruit set in tomatoes over those fertilized by honeybees or controls pollinated by wind. Thus, it can be concluded, as demonstrated in our study, that introducing solitary *Xylocopa* to open field environments can lead to increased tomato productivity due to higher visitation rates and efficiency. Additionally, recent findings revealed that some solitary bees are more effective at helping maximize crop yield across several species in particular those that need buzz pollination.

Pollination Effectiveness: Fruit Set and Yield

Fruit set was measured six weeks after anthesis and significant differences in fruit set between treatments were found. Significant differences among treatments were confirmed ($F_{3,12} = 6.72$, *P<0.01*). *Xylocopa* spp. achieved the highest fruit set. Introduction plot (85% flowers becoming fruit) was significantly higher than control plot (75%) and *Xylocopa* spp. exclusion plot (50%). The fruit set in the mixed pollination plot was 80%, comparable to that of a control plot, but lower than that of *Xylocopa* spp. introduction plot.

The largest tomatoes were obtained from the *Xylocopa* introduction plot, with a mean weight of 160 g and diameter of 6.4 cm. Unlike the *Xylocopa* spp. exclusion plot resulted in significantly smaller fruits (120 g mean weight, 5.2 cm diameter). In the control plot tomatoes had mean weight of 140 g and mean diameter of 5.8 cm. In the case of the mixed pollination plot, the tomatoes had a mean weight of 145 g and a diameter of 6.0 cm, demonstrating that mixed pollination had a positive effect on fruit size compared to the exclusion plot. One-way ANOVA revealed significant differences among treatments for fruit weight ($F_{3,12} = 7.35$, $P<0.01$) and seed number ($F_{3,12} = 5.28$, $P<0.01$) (Figure 3).

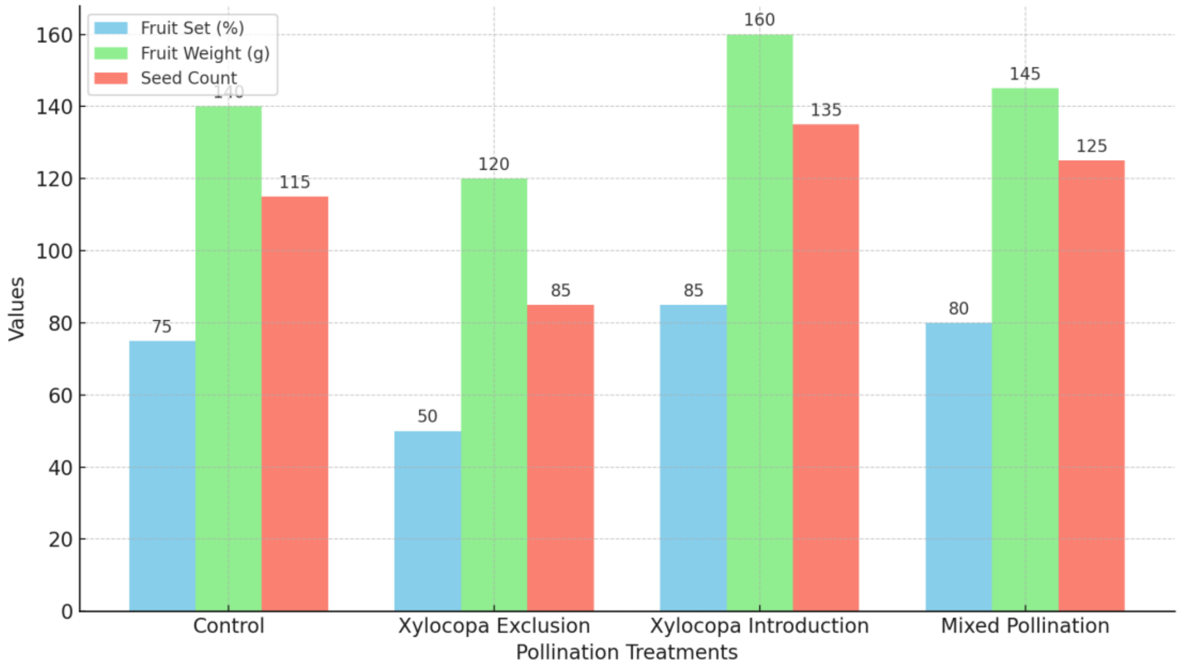

Figure 3. Effect of pollination treatments on tomato fruit characteristics

The number of seeds per fruit was significantly higher in the *Xylocopa* spp. introduction plot, with a mean number of 135 seeds per fruit. This was followed by a mixed pollination plot (125 seeds per fruit), control plot (115 seeds per fruit), and *Xylocopa* spp. exclusion plot (85 seeds per fruit). These findings indicated that the presence of *Xylocopa* spp. bees contribute to enhanced seed production and fruit development (Table 2).

Table 2. Values represent mean ± standard deviation across four replicates per treatment

Treatment	Fruit Set (%)	Average Fruit Weight (g)	Average Fruit Diameter (cm)	Average Seeds per Fruit
Control	75%	140	5.8	115
Xylocopa spp. Exclusion	50%	120	5.2	85
Xylocopa spp. Introduction	85%	160	6.4	135
Mixed Pollination	80%	145	6.0	125

Excluding *Xylocopa* resulted in significantly lower fruit set, fruit size, and seed number ($F_{3,12}$ = 6.72, *P<0.01*) (see Figure 3 and Table 2 for detailed comparison among treatments). Such results are consistent with similar patterns found in Greenleaf and Kremen (2006), which showed that wild pollinator exclusion, including that of solitary bees, led to decreased crop yields across multiple cultivars, such as tomato. This decrease was especially marked in crops that rely on particular pollinator behaviours, such as vibrational pollination, which honeybees do not perform. We also showed that when the *Xylocopa* bee could pollinate simultaneously with *Apis* sp. and stingless bee in a mixed pollination treatment, the fruit set and fruit quality were equal to those in the controls. This indicates that a diverse pollinator community might offer complementary pollination services and enhance tomato yield in the field. It has been reported Albrecht et al. (2012), that presence of multiple pollinator species are capable of increasing pollination efficiency and yield of the crops. In particular, the presence of both *Xylocopa* spp. and *Apis* sp. yielded higher pollination success relative to plots pollinated by only a single species. This results in a greater stability of yield and increased pollination efficiency in polyfloral crops with a mixed pollinator community (Hoehn et al 2008; Hünicken et al. 2021; Isaacs et al. 2017; Khalifa et al. 2021). In crops like tomatoes, which require vibrational pollination, solitary bees, such as *Xylocopa*, typically performed more efficient pollination services than honeybees.

According to the Indonesian National Standard (SNI 01-3166-1992) for tomato fruit quality, marketable tomatoes typically range between 100–160 g in weight and 5.0–6.5 cm in diameter. The average fruit size and mass observed in this study (120–160 g, 5.2–6.4 cm) fall within or exceed these marketable thresholds, indicating that the pollination treatments especially with *Xylocopa* spp. produced commercially acceptable fruit. The superior fruit weight and diameter observed in *Xylocopa* introduction plots therefore represent not merely larger size but enhanced market quality consistent with national grading standards. While larger fruit size may not inherently denote higher nutritional quality, it is a critical determinant of marketability in commercial tomato production. Therefore, the observed increase in fruit weight and diameter under *Xylocopa* pollination indicates improved yield quality within accepted commercial standards.

Statistical Analysis of Fruit Set, Fruit Weight, and Seed Development

Statistical analysis (one-way ANOVA) showed significant differences (*P<0.05*) between treatments for fruit set, fruit weight, and seed development. One-way ANOVA results confirmed significant differences among treatments for fruit set, fruit weight, and seed number ($F_{3,12}$ = 6.72, *P<0.01*; $F_{3,12}$ = 7.35, *P<0.01*; $F_{3,12}$ = 5.28, *P<0.01*). Post-hoc Tukey's test revealed that the *Xylocopa* spp. introduction plot had significantly higher fruit set, larger fruit weight, and more seeds per fruit than the *Xylocopa* spp. exclusion plot, which had the lowest values for these metrics. The control plot and mixed pollination plot also showed significant differences, but both were intermediate to the other treatments (Table 3).

Table 3. Statistical analysis of fruit set, fruit weight, and seed development (mean±SD; different superscript letters indicate significant differences between treatments, Tukey's HSD, P< 0.05)

Variable	Treatment	Mean	F-Value	*P*-Value
Fruit Set (%)	*Xylocopa* spp. (Introduction)	85%	6.72	*<0.01*
	Control	75%		
	Xylocopa spp. (Exclusion)	50%		
	Mixed Pollination	80%		

Fruit Weight (g)	*Xylocopa* spp. (Introduction)	160	7.35	*<0.01*
	Control	140		
	Xylocopa spp. (Exclusion)	120		
	Mixed Pollination	145		
Seeds per Fruit	*Xylocopa* spp. (Introduction)	135	5.28	*<0.01*
	Control	115		
	Xylocopa spp. (Exclusion)	85		
	Mixed Pollination	125		

Note: Mean±SD (n = 4). One-way ANOVA: $F_{3,12}$ values and corresponding p-values shown. Different letters denote significant differences (Tukey's HSD, *P<0.05*). Degrees of freedom for each ANOVA test: df = 3, 12 (between- and within-groups, respectively).

Our study found that tomatoes in the *Xylocopa* spp. introduction treatment were significantly larger, with higher seed counts compared to the other treatments. These results align with studies by Keasar (2010), who observed that solitary bees, such as *Xylocopa* species, demonstrate superior efficacy in pollen transfer and enhancement of seed production in crops compared to honeybees, which is attributable to their larger body size and specialized behavior. In contrast to honeybees, *Xylocopa* exhibit more focused and deliberate pollination behavior, potentially resulting in more effective fertilization and, consequently, improved seed development. Further support for this finding comes from Hünicken et al. (2021), who demonstrated that solitary bees were able to increase both fruit size and seed number in crops like tomatoes, which require high pollen transfer efficiency. Similarly, Dingley et al. (2022) reported that fruit weight and seed quality were significantly enhanced when solitary bees such as *Xylocopa* were present in pollination treatments.

Moreover, the substantial increase in fruit weight (160 g in the introduction treatment) compared to the control (140 g) and exclusion treatments (120 g) indicates that *Xylocopa* contribute not only to the quantity of fruit set but also to the overall fruit quality. This is supported by Franceschinelli et al. (2013), who found that pollination by solitary bees resulted in heavier fruit and higher-quality seeds compared to other pollinators, likely due to the longer and more effective foraging visits that *Xylocopa* bees typically make.

Environmental Variables

Throughout the study, environmental conditions such as temperature, relative humidity, and wind speed were monitored. Temperature ranged from 26 °C to 32 °C, relative humidity 60–70 %, and mean wind speed 2.1 m/s. The mean temperature during the study period was 28°C, with a relative humidity of 65% and mean wind speed 2.1 m/s. No statistically significant correlation was observed between these environmental variables and the observed differences in fruit set or fruit quality, suggesting that the effects were primarily attributable to pollination treatments.

Our results suggest that incorporating *Xylocopa* into open-field agricultural systems could be a promising strategy for increasing tomato yield, especially in areas with dwindling honeybee populations. Since solitary bees such as *Xylocopa* do not compete with honeybees for floral resources, these bees can be considered a promising alternative for supplementing pollination services in some crops where specific pollination mechanisms, such as buzz-pollination, are needed. In addition, *Xylocopa* bees for tomato pollination is eco-friendly because these bees do not need intensive management practices like commercial honeybees. The results of this study have important practical implications for enhancing pollination services provided to commercial tomato crops. The potential for the introduction of *Xylocopa* species or developments that enhance the conservation of these bees within agricultural landscapes to reinforce the resiliency of tomato crops against pollinator shortages, and result in greater and more consistent yields, was thus demonstrated. These solitary bees are increasingly seen as an important player in sustainable farming methods in light of their higher pollination efficiency (Eeraerts et al. 2020a; Pardo & Borges 2020) and less vulnerability to the problems that afflict honeybee colonies managed by humans (Eeraerts et al. 2020b; Kevan et al. 1990). Given that the concerns about global pollinators are increasing, the preservation and use of wild pollinators, including solitary bees, should become incorporated into good agricultural practice. This can be achieved by increasing pollinator forage through the planting of pollinator friendly vegetation, reduction of pesticide use (Samsudin et al. 2024), and implementing beekeeping practices that have benefits for native bee populations.

CONCLUSION

Xylocopa introduction increased fruit set to 85 % compared to 50 % in exclusion plots and improved mean fruit weight from 120 g to 160 g, confirming its strong positive impact on yield. The buzz pollination behavior of *Xylocopa* bees enables superior pollen transfer, resulting in better fruit quality and higher yields. Plots where *Xylocopa* bees were introduced achieved the highest performance across all measured parameters, while their exclusion led to marked declines. These findings underscore the critical role of *Xylocopa* in sustainable agriculture and highlight the importance of conserving and integrating solitary bees into pollination strategies to ensure resilient and productive cropping systems. Although this study demonstrates the effectiveness of *Xylocopa* bees, further studies are required to address remaining limitations, including comparisons with other solitary bee species and long-term ecosystem effects. For example, even though the current research was centered around *Xylocopa* spp., there is quite a number of solitary bees that can show different levels of pollination efficacy. Comparative studies of the effectiveness of solitary bee species are needed in the future to understand their relative contribution to crop pollination. Additional research on the long-term effects of adding *Xylocopa* to ecosystem service and biodiversity in agricultural landscapes will be important. In fact, its been suggested that promoting pollinator habitat may simultaneously promote natural enemies of crop insect pests, leading to synergistic effects for overall crop health and production.

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AUTHORS DECLARATION

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Conflict of Interest
The authors declare that there is no conflict of interest regarding the conduct of this research or the publication of this article.

Ethics Declaration
Ethical considerations were an important part of this study, particularly regarding the handling of *Xylocopa* bees. All procedures were conducted in accordance with the established ethical guidelines for the study of pollinators. No bees were harmed during the research process, and the use of managed habitats for *Xylocopa* was designed to ensure the welfare of bees. Additionally, the study adhered to the environmental guidelines for insect population management, ensuring that no disruption occurred in the local pollinator community.

Data Availability Statement
All data supporting the findings of this study are included within the article.

Author's contribution
A.G.M.I.S. conceived and designed the study, supervised all research activities, and led the manuscript writing. S.D.R and A.G.M.I.S. conducted field sampling, trap deployment, and specimen preservation. S.D.R. performed data organization, biodiversity index calculation, and contributed to figure and table preparation. All authors contributed to data interpretation, critically reviewed the manuscript, and approved the final version for submission.

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