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RESEARCH PAPER

Augmentorium devices: A sanitation tools for control fruit flies and augmentation parasitoids of fruit flies on chilli plants

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ABSTRACT

Fruit flies, *Bactrocera* spp. (Diptera: Tephritidae), cause severe yield losses in chili production and conventional insecticide-based control raises environmental and resistance concerns. To our knowledge, this study was the first field evaluation in Indonesia to measure the mesh size threshold for an augmentorium that simultaneously retains newly emerged adult Bactrocera insects and allows for the release of naturally occurring parasitoids. This research aimed to identify fruit fly parasitoid species found in chili (*Capsicum frutescens* L.) fields and recommend mesh sizes that would enable parasitoids to pass through augmentation devices. This study was conducted in Balung District and the Agrofarmaka Laboratory of Jember University, Jember Regency, East Java, Indonesia. Infested chili fruits were placed in augmentorium devices fitted with four mesh diameters 0.5 mm/32 Mesh; 0.75 mm/24 Mesh; 1 mm/16 Mesh; and.5 mm/12 Mesh. Observations were made by identifying parasitoid species and counting the number of emerging parasitoids. The results showed the presence of two parasitoids, *Psyttalia fijiensis* and *Trichopria* sp., which successfully emerged from samples and passed through the meshes. *P. fijiensis* was able to traverse only the largest mesh (1.5 mm), whereas *Trichopria* sp. passed even the smallest mesh (0.5 mm). Based on these results, the 1.5 mm (12-mesh) augmentorium optimizes its dual function as a sanitation tool for fruit infested with fruit flies and as a parasitoid augmentation in chili cultivation. This evidence supports the practical application of augmentorium as a landscape-scale celement in integrated pest management for *Bactrocera* spp. is supported by this evidence.

Keywords: Augmentation device, fruit fly, netting, parasitoid, sanitation tool

INTRODUCTION

Fruit flies (*Bactrocera* spp.) (Diptera: Tephritidae) are among the major insect pests of horticultural crops. They are polyphagous pests that attack various types of fruits and vegetables. In Indonesia, numerous fruit commodities have been infested *Bactrocera* fruit flies, including mango, orange, papaya, guava, and chili pepper (Abdullah et al., 2021; Octavia et al., 2021; Susanto et al., 2022; Tarno et al., 2022). Fruit fly infestation in chili plants is characterized by black spots on the fruit caused by oviposition, after which the eggs develop into larvae inside the fruit (Herlinda et al., 2007). Fruit fly attacks can reduce chili productivity by up to 70%, thereby failing to meet national demand (Hodiyah & Hartini, 2019).

Fruit fly traps and synthetic insecticide applications are standard methods used by farmers to control fruit flies. However, these techniques have several limitations. Fruit fly traps still rely primarily on male attractants (methyl eugenol), while synthetic insecticides may lead to insect resistance, mortality of non-target organisms, and pesticide residues in agricultural products (Beers et al., 2016; Guedes, 2017; Sivaperumal et al., 2015). Across Asia, fruit fly populations have developed resistance to several active ingredients, including fenitrothion, fenthion, malathion, naled, and trichlorfon, highlighting the need for more sustainable control alternatives (Jin et al., 2011). The use of synthetic pesticides has also been shown to reduce natural enemy populations, resulting in lower insect equitability compared with biopesticide use (Sanjaya & Dibiyantoro, 2012). Populations of fruit

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fly parasitoids *Fopius arisanus* and *Psyttalia fletcheri* are particularly affected by the application of synthetic pesticides such as pyrethroids and organophosphates (Rousse et al., 2006; Deguine et al., 2011). Therefore, improved management strategies are needed to control fruit flies in chili crops.

Biological control can help maintain the stability of insect populations and preserve the integrity of food chains and food webs in natural ecosystems (Lucatero & Philpott, 2024; Sanjaya & Dibiyantoro, 2012). Sanitation is one control method that involves the collection and destruction of infested fruit in the field to break the fruit fly life cycle. However, although sanitation reduces pest populations by removing larva-infested fruit, it can also inadvertently eliminate parasitoids developing within the hosts, thereby disrupting the buildup of parasitoid populations needed for effective biological control. Consequently, integrating multiple control methods is necessary (Kehrli et al., 2005; Reddy et al., 2020).

Combining two complementary approaches—direct pest suppression and augmentation of natural enemies—offers a promising synergistic strategy. This underscores the need to evaluate augmentation devices capable of retaining fruit flies while allowing parasitoids to escape. Such devices have been tested on the pest *Nezara viridula*, successfully retaining the pest while releasing its parasitoids (Hikmah & Purnomo, 2020). A key factor determining the success of augmentation devices is the selection of mesh sizes that can retain fruit flies but permit the passage of their parasitoids. Kehrli et al. (2005) reported that parasitoid augmentation devices are equipped with nets of various mesh sizes. Augmentorium research targeting fruit flies has been conducted in Hawaii (Jang et al., 2007) and on Réunion Island in the Indian Ocean (Deguine et al., 2011). In Indonesia, similar studies have been performed on the pest–parasitoid complex of the green stink bug on soybean (Hikmah & Purnomo, 2020).

This study aimed to (1) identify the principal parasitoid species associated with *Bactrocera* spp. in chili (*Capsicum frutescens* L.) crops and (2) quantitatively evaluate the mesh-size thresholds of an augmentorium that simultaneously retain emerging adult *Bactrocera* spp. while allowing parasitoid escape. This work provides the first quantitative evaluation of mesh performance under chili production conditions by explicitly integrating species-specific body size and foraging ecology to derive practical mesh recommendations for integrated pest management. In contrast to previous augmentorium studies that primarily focused on fly exclusion and operational feasibility in island systems (Deguine et al., 2015; Desurmont et al., 2022; Githiomi et al., 2019; Jang et al., 2007; Klungness et al., 2005), we hypothesized that mesh size correlates with parasitoid morphology and behavior in determining passage success, and that an optimal mesh will balance the trade-off between pest sequestration and parasitoid conservation.

MATERIALS AND METHODS

Research Site. This research was conducted in Balung District and at the Agrofarmaka Laboratory, University of Jember, Jember Regency, East Java, Indonesia. The study was carried out from from October to December 2023.

Augmentation Device Development. Augmentation devices were constructed using 15-L gallon containers fitted with bottles at the top (Figure 1). Holes were drilled at the bottom of each container to allow water drainage, and small holes were also made at the top to ensure air circulation. The bottle attached to the top was divided into four compartments, each fitted with mesh. Mesh diameters were measured using a Nikon Stereo Microscope SMZ 745 and calibrated with Raster Image Software to determine the diameter of each mesh. The meshes used had diameters of 0.5 mm (32 mesh), 0.75 mm (20 mesh), 1.0 mm (16 mesh), and 1.5 mm (10 mesh) (Figure 2).

Collection of Fruit Fly–Infested Fruit. Sampling was conducted in Balung District, Jember (8°16’44.4”S 113°29’59.1” E). Chili fruit samples were collected from ORI 212 plants cultivated under Integrated Pest Management (IPM) practices. Fruit samples were taken from 12-week-old plants at five sampling times conducted at 10-day intervals. At each sampling time, 80 chili fruits were collected. Purposive sampling targeted chili fruits infested with fruit flies, as indicated by black spots or blemishes. The collected chili fruits were placed in plastic bags (12 cm × 25 cm) labeled with the date and location of collection.

Collection of Parasitoids. The collected fruit samples were placed inside the augmentation device and kept until parasitoids or fruit flies emerged and moved upward through the device. Parasitoids were collected from the different mesh layers and subsequently identified to species level. Identification was performed using the website http://paroffit.org/, Hymenoptera of the World: An Identification guide to families, and Taxonomy and Biology of Parasitic Hymenoptera. The identification

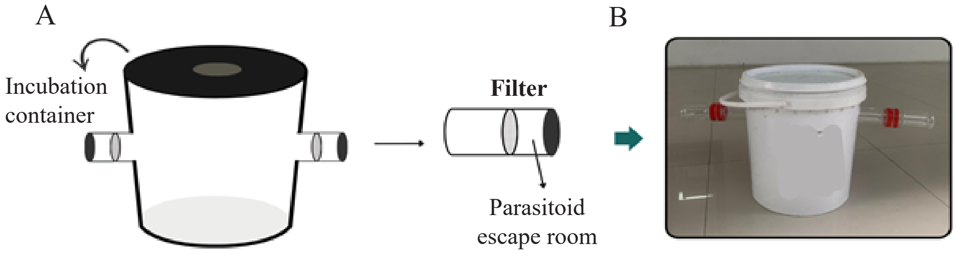

Figure 1. Augmentation device design and implementation. A. Prototype design of the augmentation device; B. Implementation of the augmentation device.

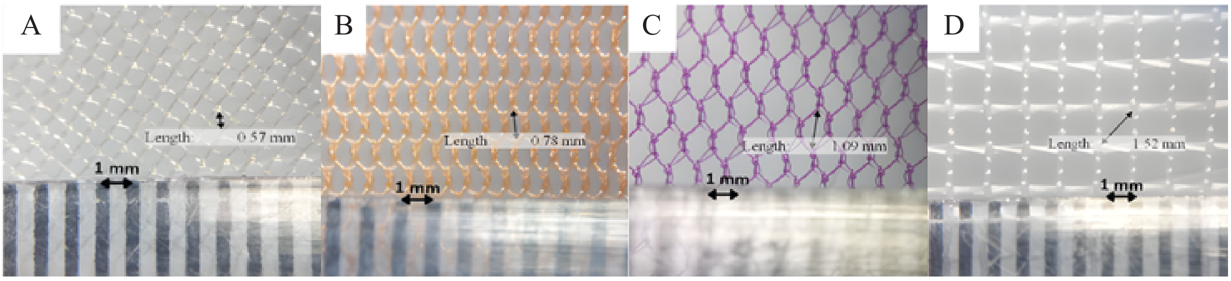

Figure 2. Mesh diameter sizes used in the study. A. 0.5 mm (32 mesh); B. 0.75 mm (20 mesh); C. 1.0 mm (16 mesh); D. 1.5 mm (10 mesh).

process included microscopic observation, specimen documentation, and morphological analysis.

Experimental Design. A Completely Randomized Design (CRD) was used in this experiment. The tested factor was mesh size of the barrier in the augmentation device, consisting of four levels: 0.5 mm (32 mesh) (P1), 0.75 mm (20 mesh) (P2), 1.0 mm (16 mesh) (P3), and 1.5 mm (10 mesh) (P4). Each treatment was replicated five times. The observed variables included fruit fly population, parasitoid population and species, parasitoid parasitism rate on fruit flies, and the effectiveness of the barrier mesh for parasitoid emergence. The parasitism rate was calculated using the following formula (Rauf, 2000) :

$$P = \frac{A}{A + B} \times 100\%$$

P = Parasitism rate (%);
A = Number of parasitized fruit flies;
B = Total number of fruit flies.

Data Analysis. The effectiveness of the barrier mesh for parasitoid emergence was analyzed using Analysis of Variance (ANOVA). When the ANOVA indicated significant differences, mean separation was performed using the Honestly Significant Difference (HSD) test at the 95% confidence level.

RESULTS AND DISCUSSION

Parasitoid Species and Numbers. The study revealed two parasitoid species that successfully passed through the mesh treatments: *Psyttalia fijiensis* and *Trichopria* sp. The morphology of *P. fijiensis* is characterized by: (a) wings with numerous veins and cells; (b) the presence of the RS+M vein but the absence of the 2m–cu vein; (c) mandibles narrowed at the tip and overlapping when closed; and (d) a large second submarginal cell (Pujiastuti, 2009) (Figure 3). *P. fijiensis* belongs to the subgenus *Opius* (Wharton & Gilstrap, 1983) and is a parasitoid of chili fruit flies, parasitizing hosts by ovipositing into the larval stage (Herlinda et al., 2007; Lukman, 2009).

The second parasitoid identified in this study was *Trichopria* sp. Its morphology includes: (a) wings with reduced venation; (b) veins with varying degrees of development, lacking a postmarginal vein and veins in the distal half of the wing; (c) a normal scutellum without a dorsal plate, and wings with reduced venation, sometimes showing small head-like spots; (d) females with 12-segmented antennae and males with 14-segmented antennae; and (e) straight mandibles, unfolded wings, and distinct submarginal veins ending at the anterior wing margin (Shimbori et al., 2020) (Figure 4).

Trichopria sp. is classified in the family Diapriidae, subfamily Diapriinae (Hymenoptera). Most species are pupal parasitoids (Gomina et al., 2020; Vieira et al., 2020a; Vieira et al., 2020b). *Trichopria* may parasitize larvae when host pupation is delayed or when environmental conditions cause overlap between developmental stages (Colombari et al., 2020). Its primary parasitism occurs at the pupal stage, where it exhibits solitary development (one parasitoid per host) (Buonocore-Biancheri et al., 2024).

The proportion and abundance of parasitoid species are influenced by host developmental stage and host availability. The percentage of *P. fijiensis* (36%; 91 individuals) was higher than that of *Trichopria* sp. (8%). Similarly, the parasitism rate of *P. fijiensis* exceeded that of *Trichopria* sp. (Table 1). The high parasitism rate of *P. fijiensis* is attributed to *Bactrocera* spp. being its primary host and to its superior performance compared with other larval parasitoids (Dieng et al., 2020). *Psytallia* spp. are major parasitoids of fruit flies and are frequently reported parasitizingg *B. dorsalis,* with parasitism rates 25–30% higher than those of parasitoids such as *Fopius* spp. and *Opius* spp. (Lin et al., 2021; Wang et al. 2021; Herlinda et al., 2007). In contrast, *Trichopria* sp., as a pupal parasitoid, has a broad host range within Diptera, with Drosophilidae as its primary hosts (Wang et al., 2016; Colombari et al., 2020), although it has also been reported from Tephritidae, including the genera *Ceratitis*, *Anastrepha*, and *Bactrocera* (da Costa Oliveira et al., 2021; Shimbori et al., 2020). Some studies report parasitism levels of *Trichopria* sp. reaching 51.3%, exceeding those of parasitoids such

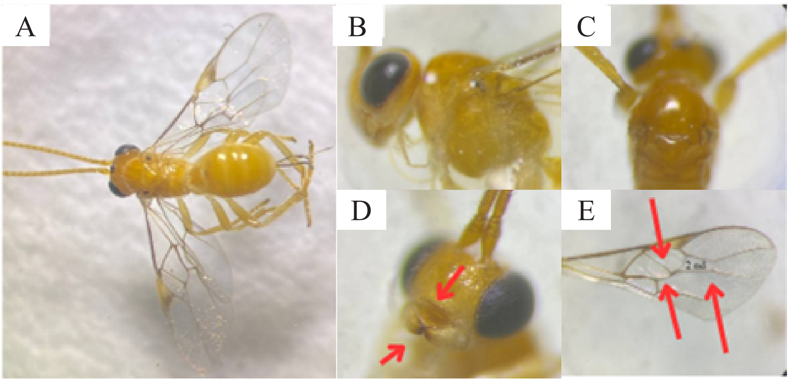

Figure 3. Diagnostic morphological features of *P. fijiensis*. A. General morphology of *P. fijiensis*; B. Sternaulus absent; C. Mesonotum with notauli present; D. Overlapping mandibles; E. RS+M vein present and 2m–cu vein absent.

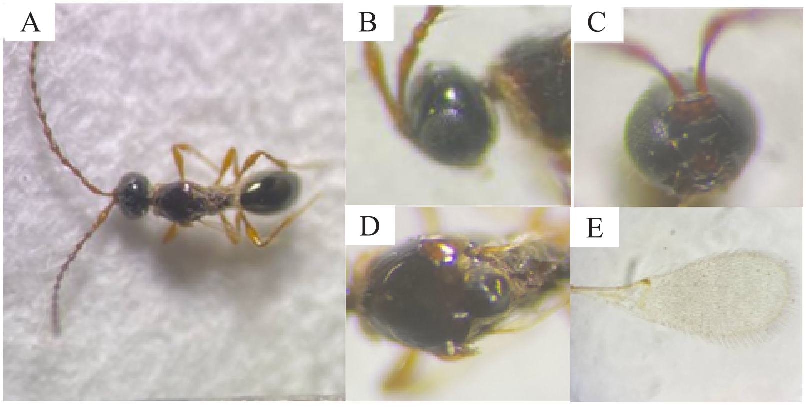

Figure 4. Diagnostic morphological features of *Trichopria* sp. A. General morphology of *Trichopria* sp.; B. Head of *Trichopria* sp.; C. Non-curved mandibles; D. Normal scutellum; E. Wings with reduced venation.

Table 1. Number and parasitism rate of fruit fly parasitoids at each observation time

Observation	Fruit flies	Parasitoid		Total population	Parasitation rate (%)		
		P. fijiensis	*Trichopria* sp.		*P. fijiensis*	*Trichopria* sp.	Total
1	31	20	6	57	35	11	46
2	25	11	13	49	22	27	49
3	36	24	1	61	39	2	41
4	29	24	0	53	45	0	45
5	21	12	0	33	36	0	36
Total	142	91	20	253	36	8	44

as *Diachasmimorpha fullawayi, Fopius caudatus, Asobara* sp., *Aganaspis* sp., *Pachycrepoideus vindemmiae, Spalangia* sp., *Tetrastichus giffardianus* and *Dirhinus giffardii* (Gomina et al., 2020; Woltering et al., 2019). Under laboratory conditions, *Trichopria* spp. can reach parasitism levels of up to 90% (Allan et al., 2022; Istas & Szűcs, 2023).

Psyttalia spp. are solitary koinobiont endoparasitoids that search for hosts using cues from infested fruit and attack early larval stages. In contrast, *Trichopria* sp. is a solitary idiobiont pupal parasitoid targeting the pupal stage, typically in lower substrates such as soil or organic matter. In this study, *P. fijiensis* was more dominant than *Trichopria* sp. This pattern may relate to the more restricted geographic distribution of *Trichopria* sp. (Gomina et al., 2020) and to differences in demographic traits such as generation time, developmental rate, and habitat requirements (pupation in soil), which can reduce field success and lead to localized distributions (Chen et al., 2018; Funes et al., 2024).

Parasitoids of the genus *Psyttalia* attack earlier larval stages and may exert priority effects (early-acting competitive superiority) or intraguild suppression, thereby reducing the likelihood that later-acting pupal parasitoids such as *Trichopria* sp. successfully develop in the same host (Pinheiro et al., 2022; Cuny & Poelman, 2022). Early host occupation by koinobiont larvae can therefore suppress subsequent parasitism by pupal parasitoids. *P. fijiensis* locates hosts using herbivore-induced plant volatiles (HIPVs), which increase encounter rates (Bogka et al., 2023). In contrast, *Trichopria* sp. targets pupae enclosed within puparia, often located in soil and emitting weaker volatile cues, which may limit field access despite high laboratory parasitism potential (Wang et al., 2016; Allan et al., 2022). Consequently, field encounter probability is likely higher for *P. fijiensis* than for *Trichopria* sp.

An effective control strategy should exploit the complementary roles of both parasitoids: *Psyttalia* as the primary suppressor of the reproductive population and *Trichopria* sp. as a secondary agent targeting residual pupae in the substrate. Practical implementation may include habitat conservation (e.g., nectar sources or flower strips to extend parasitoid longevity), sanitation of infested fruit using appropriately sized augmentoria that retain flies but release parasitoids, reduced soil disturbance in pupation zones to favor *Trichopria*, and synchronization of augmentations with peak fruiting periods. This landscape-scale approach is expected to provide more comprehensive suppression of *Bactrocera* spp. (Bogka et al., 2023; Desurmont et al., 2022; Ode et al., 2022; Istas & Szűcs., 2023).

Eficacy of the Mesh for Parasitoid Exit. This study evaluated mesh sizes capable of retaining adult fruit flies while allowing parasitoids to escape. *P. fijiensis* passed through the barrier mesh primarily at 1.5 mm (12 mesh; P4), whereas *Trichopria* sp. successfully passed through the through the 0.5 mm (32 mesh; P1) treatment. The percentage of parasitoid passage was 0.9% (1 individual) in P1, 7.2% (8 individuals) in P2, 18% (20 individuals) in P3, and 100% (111 individuals) in P4. None of the mesh treatments allowed passage of adult fruit flies (Table 2).

All parasitoids successfully passed through the P4 mesh. *P. fijiensis* showed limited passage through P3 (1.8%), whereas *Trichopria* sp. passed through P2 and P1 at rates of 7% and 1%, respectively. Differences in passage rates among species were primarily attributable to body size differences (Table 3). Adult *Bactrocera* spp. are generally larger than the two parasitoids, indicating that appropriate mesh selection is critical to simultaneously trap fruit flies and permit parasitoid escape. Variation in passage among treatments reflects interspecific size differences, consistent with previous studies (Table 2) (Deguine et al., 2011; Kehrli et al., 2005; Desurmont et al., 2022; Ingwell et al., 2018).

ANOVA indicated significant differences among treatments ($P < 0.05$, $P = 0.000$). Tukey's HSD test showed that the 1.5 mm mesh (P4) differed significantly

Table 2. Number of parasitoid passing through each treatment

Parasitoid types	Treatment			
	P1	P2	P3	P4
P. fijiensis	0	0	2	91
Trichopria sp.	1	8	18	20
Number of individuals	1	8	20	111
P. fijiensis	0%	0	1.8%	82%
Trichopria sp.	1%	7%	16.2%	18%
Percentage of passage	1%	7%	18%	100%

from all other treatments (P1–P3) (Table 4). Thus, the 1.5 mm (12 mesh) barrier was the most effective configuration, preventing adult fruit fly escape while allowing parasitoid passage.

Determining suitable mesh sizes supports the development of sanitation tools for fruit fly management and parasitoid augmentation. Such devices may also function as monitoring tools for fruit fly–parasitoid dynamics (Kehrli et al., 2005). Previous mesh studies have been conducted mainly in Hawaii, La Réunion, parts of Africa, and southern France (Domaine de l'Oulivie, Combaillaux, Hérault, France) (Deguine et al., 2015; Desurmont et al., 2022; Githiomi et al., 2019; Jang et al., 2007; Klungness et al., 2005). Similar work has involved fruit flies such as *Ceratitis capitata, Bactrocera cucurbitae, Bactocera oleae,* and *Bactrocera zonata,* with parasitoids *Fopius arisanus, Psyttalia fletcheri, Psyttalia lounsburyi,* and *Psyttalia ponerophaga* (Deguine et al., 2011; Desurmont et al., 2022).

Mesh-based systems must account for variation in fruit fly body size across host plants and for species-specific behavioral traits. Consequently, universal application across pest–parasitoid complexes may be limited (Deguine et al., 2011). Successful mesh design depends on a clear size differential between pest and parasitoid, ensuring effective pest retention while permitting natural enemy escape.

In this study, bucket containers with sterile sand were used to support fruit fly pupation and optimize development of both flies and parasitoids, consistent with (Desurmont et al., 2022). Containers were covered with black material to promote upward insect movement toward the mesh. For future development, fruit incubation containers could be adapted for direct field deployment and improved monitoring functionality.

Barrier mesh systems also have potential as sanitation tools for managing infested fruit within IPM programs (Klungness et al., 2005; Vargas et al., 2008). Because discarded infested fruit may contain developing parasitoids, integrating mesh-based sanitation with parasitoid conservation could enhance biological control (Rossi-Stacconi et al., 2019). Additionally, these devices may function as composting units for decomposed fruit residues, although compost quality and potential contamination by pathogenic fungi such as *Penicillium* sp. must be considered (Deguine et al., 2011).

Overall, the device shows multifunctional potential in fruit fly management, including sanitation, parasitoid conservation, and compost production. Future research should evaluate performance under semi-field and open-field conditions and compare effectiveness with conventional approaches such as methyl eugenol–baited traps and non-augmentation biological control.

CONCLUSION

The findings of this study indicate that adult *Bactrocera* spp. can be efficiently retained in an augmentorium with a 1.5 mm mesh size (12 mesh) while still allowing the escape of parasitoids, particularly *P. fijiensis* and *Trichopria* sp., which are commonly found in chili-growing areas. These results demonstrate that appropriate mesh selection can achieve two key objectives: (1) removing infested fruit while preventing the escape of fruit flies, and (2) facilitating the release of natural parasitoids to support field-level biological control. In other words, a simple but properly designed augmentorium can disrupt the fruit fly life cycle without compromising the ecological benefits provided by natural enemies. This study offers

Table 3. Body size ranges of fruit flies and parasitoids

Insects	Head width (mm)	Thorax width (mm)	Abdomen width (mm)
Bactrocera spp.	2.01–2.10	2.17–2.23	2.07–2.20
P. fijiensis	0.91–1.04	0.82–0.96	0.81–0.97
Trichopria sp.	0.46–0.70	0.33–0.45	0.43–0.62

Table 4. Tukey's test for barrier mesh size treatments

Treatment	Mean parasitoid passage (individuals)	Notation
P1 0.5 mm / 32 Mesh	0.2	a
P2 0.75 mm / 24 Mesh	1.6	a
P3 1.0 mm / 16 Mesh	4.0	b
P4 1.5 mm / 12 Mesh	22.2	b

practical support for integrated pest management (IPM) implementation, particularly given that routine use of synthetic pesticides may negatively affect parasitoids and increase the risk of pest resistance.

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AUTHORS' CONTRIBUTIONS

WM and IS designed the research. WM supervised all the processes, and AT and MU collected the data. WM, ILIP, and MU analyzed the data. WM and AT wrote the manuscript. All the authors have read and approved the final manuscript

COMPETING INTEREST

All authors declare that there are no competing interests.

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