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Original Article

New parasitoids of *Spodoptera frugiperda* in Lampung Province, Indonesia

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ABSTRACT

Lampung Province is one of the largest maize producers in Indonesia. The invasion of *Spodoptera frugiperda* into Indonesia led to damage in maize, thereby impacting production. In the invaded area, native natural enemies also played a role in controlling the population of *S. frugiperda*. Therefore, the exploration and identification of parasitoids associated with *S. frugiperda* were necessary to determine potential control strategies. Four species of parasitoids were discovered emerging from *S. frugiperda* larvae collected from four maize production areas in Lampung Province, Indonesia, i.e. Lampung Timur, Pesawaran, Pringsewu, and Lampung Selatan. The parasitation rate ranges from 3.17 to 4.81%. Morphological observations confirmed that the parasitoids belonged to the genera *Senometopia* (Diptera: Tachinidae), *Eriborus* (Hymenoptera: Ichneumonidae), *Chelonus* (Hymenoptera: Braconidae), and *Drino* (*Palexorista*) (Diptera: Tachinidae). Additionally, Cytochrome C Oxidase Subunit I (COI) sequence analysis revealed that the parasitoids were identified as *Senometopia illota*, Genus nr. *Eriborus* sp., *Chelonus formosanus*, and *Drino* (*Pelexorista*) sp. *Senometopia illota* and Genus nr. *Eriborus* sp. are newly recorded as parasitoids of *S. frugiperda*. This finding will provide valuable information concerning the global diversity and distribution of parasitoids, including Indonesia, as well as a basis for determining appropriate control strategies for *S. frugiperda*.

Introduction

Lampung Province is one of the largest maize producers in Indonesia (Indonesian Central Bureau of Statistics 2023), boasting a production rate of 60 qu/ha, which exceeded the national average of 54.75 qu/ha in 2021 (Astuti et al. 2021). The invasion of *Spodoptera frugiperda* into Indonesia significantly harmed maize plants, impacting overall production. *S. frugiperda* is native to the tropical region of South America (Cruz et al. 1999). The first invasion of this pest was reported in Africa in 2016, specifically in Central and Western Africa (Goergen et al. 2016).

In 2018, *S. frugiperda* caused damage to maize in India (Sharanabasappa et al. 2018), Myanmar, Thailand (IPPC 2018; Ma et al. 2019), and Yunnan Province, China (Xiao-xu et al. 2021). In Indonesia, *S. frugiperda* was discovered for the first time on Sumatra Island, including West Sumatra (Nonci et al. 2019; Sartiami et al. 2020) and Lampung (Trisyono et al. 2019; Lestari et al. 2020), subsequently spreading throughout the country (Maharani et al. 2019; Sartiami et al. 2020). The pathway of this pest's interception remains unclear due to the absence of records regarding international maize trade with Sumatra Island.

Following the invasion of *S. frugiperda*, various natural enemies were also found controlling the populations in the invaded area. In their native regions in the Americas and the Caribbean basin, approximately 150 species were identified as natural enemies of *S. frugiperda* (Molina-Ochoa et al. 2003). Currently, several larval parasitoids of *S. frugiperda* have been identified in various countries. These include *Campoletis chlorideae* (Shylesha et al. 2018; Sharanabasappa et al. 2019), *Glyptapanteles creatonoti* (Shylesha et al. 2018), *Coccygidium melleum*, *Eriborus* sp., *Exorista sorbillans*, *Odontepyris* sp. (Sharanabasappa et al. 2019) in India, *Megaselia scalaris* in China (Tang et al. 2021) and India (Deshmukh et al. 2021), *Drino quadrizonula* in Uganda (Otim et al. 2021), Mozambique (Caniço et al. 2020), and Benin (Kenis et al. 2019).

The presence of larvae parasitoids of *S. frugiperda* has also been reported in certain areas of Indonesia, such as Sumatera Barat i.e.

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Microplitis sp. and *Chelonus* sp. (Sari et al. 2023), Nusa Tenggara Barat i.e. *Apanteles* spp., *Eriborus* spp., and *Exorista* spp. (Supeno et al., 2021), and in Sumatera Selatan, a total of twelve species of larval parasitoid have been identified to parasitize *S. frugiperda* including *Chelonus formosanus* Sonan, *Chelonus oculator* F., *Chelonus annulipes* Wesm., *Chelonus cautus* Cresson, *Microplitis anila* Ashmead, *Microplitis marshallii* Kokujev, *Euplectrus corriemoreauae* Hansson, *Compsilura concinnata* Meigen, *Sarcophaga* sp., *Macrocentrus* sp., *Exorista* sp., and *Megaselia* sp. (Herlinda et al. 2023). Therefore, the current investigations aim to find new *S. frugiperda* larval parasitoids in Lampung Province. The findings obtained in this research will provide valuable insight into the global diversity and distribution of parasitoids, including in Indonesia. Furthermore, it lays the groundwork for formulating appropriate control strategies for *S. frugiperda*.

Material and methods

Sampling location

Observations and sampling were carried out in several locations as maize production areas in Lampung Province, namely Lampung Timur (−5°3′52.488″ S 105°21′42.363″ E), Pesawaran (−5.227467, 105.1212734), Pringsewu (−5.257742, 105.0382401), and Lampung Selatan (−5.38363666, 105.39858935) (Figure 1). Exploration was conducted from March 2021 until December 2022.

The collection of S. frugiperda *larvae and observation of emerging parasitoids*

The exploration of parasitoids was conducted by collecting the larvae of *S. frugiperda*, which were sampled from maize plants aged 30–45 days after planting. These collected larvae were reared and observed in a laboratory setting to monitor the emergence of parasitoids. Each larva was placed in an individual plastic jar (18 cm in diameter and 20 cm in height) and their diet comprised young corn leaves, which were changed daily. Daily observations were performed to monitor the emergence of parasitoids. The emerging parasitoids were then collected and preserved in a 70% alcohol solution for further investigation.

Morphological identification

Morphological identification was conducted using a stereo microscope LEICA EZ4HD with 30× magnification. Identification was carried out based on various morphological characteristics, i.e. color, front wings, the fringe of seta length, the number of trichia in remigium, hairs of the antenna, antenna shape, and length of the ovipositor. Identification of Braconidae parasitoids followed van-Achterberg (1993) and Gupta et al. (2020); Ichneumonidae was followed by Broad (2011); and Tachinidae adhered to the guidelines outlined in Tschorsnig and Herting (1994). The identified parasitoids were deposited in the Plant Pest Laboratory, Faculty of Agriculture, University of Lampung (PPLC).

DNA extraction

DNA extraction was carried out following Lestari et al. (2020), with slight modifications of the TNES buffer content (2.5 mL Tris HCl 1 M; 4 mL NaCl 5 M; 2 mL EDTA 0.5 M; 40.25 mL water distillation; and 1.25 mL SDS). The DNA was extracted from the abdomen of the parasitoid.

DNA amplification

The Sensoquest Thermal Cycle (Sensoquest, Germany) was used for PCR amplification. DNA amplification was carried out in a total

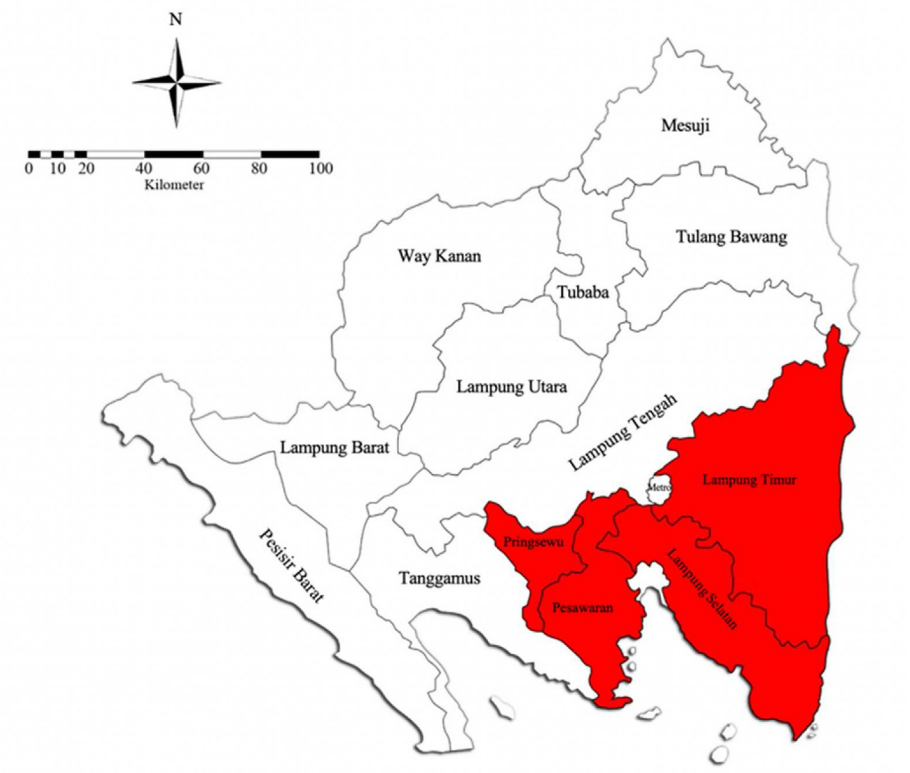

Figure 1. Observation and sampling location. The red color indicates the location of the collection of *S. frugiperda* larvae.

volume of 25 μL containing 12.5 μL of master mix (2× MyTaq HS Red Mix), 1 μL of each primer, LCO 2198 and HCO 1490 (White et al. 1990), 1 μL of DNA template, and 9.5 μL of sterile distilled water. The PCR was carried out in 1 cycle of initiation at 95 °C for 5 min, followed by 30 cycles of denaturation at 95 °C for 1 min, primer annealing at 48 °C for 1 min, primer extension at 72 °C for 1 min, and 1 cycle of elongation at 72 °C for 5 min, and then ended with one holding cycle at 4 °C for 1 min. Electrophoresis was carried out on a 0.5% agarose gel containing 1 μL EtBr at 55 volts for 60 min. The DigiDoc UV transilluminator (UVP, USA) was used to visualize the results.

Sequencing and phylogenetic analysis

The PCR products were then sent to 1st Base Malaysia. Sequencing results were analyzed using the Bio Edit program

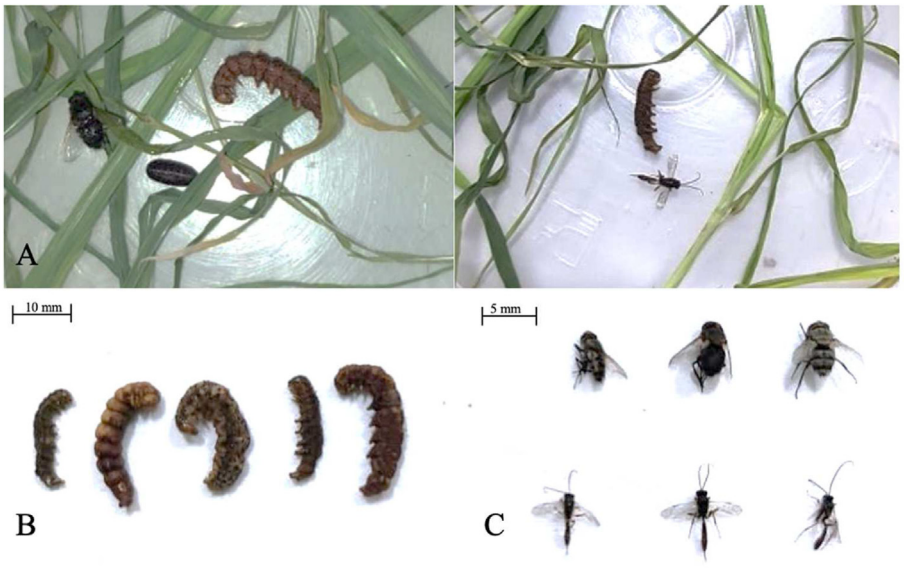

Figure 2. Larval parasitoid of *S. frugiperda*; A. Parasitoid emerged from the larvae; B. Dead larva of *S. frugiperda* after parasitoid had emerged; C. Tachinidae (above) and Inchenumonidae (below).

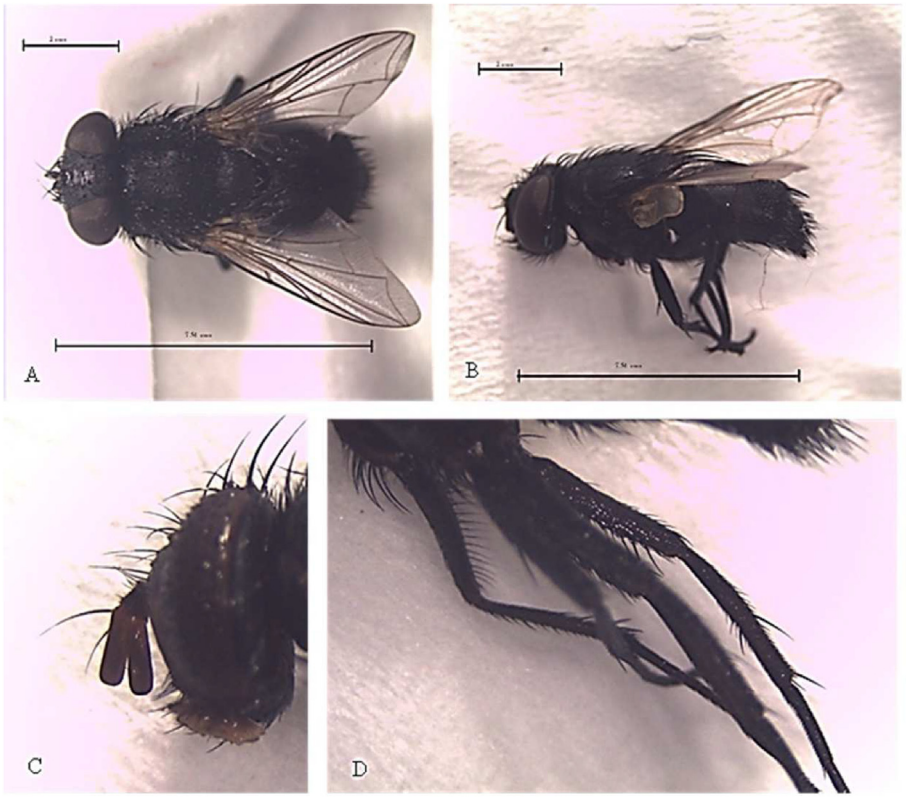

Figure 3. *S. illota* (Diptera: Tachinidae); A. Dorsal view; B. Lateral view; C. Around the eyes densely of hair; D. Legs are black.

version 7.2.6 for Windows (Hall 1999) and then submitted to the Basic Local Alignment Search Tool (BLAST) (https://blast.ncbi.nlm.nih.gov/Blast.cgi) and Barcode of Life and Data System (BOLD) (http://boldsystems.org/index.php/IDS_OpenIdEngine) to disclose the probability of the identity of the parasitoids. The phylogenetic tree was constructed using the Mega X program for Windows by the Maximum Likelihood (ML) method (General Time Reversible Model, GTR) with a 1000× bootstrap value (Nei and Kumar 2000; Tamura et al. 2012; Kumar et al. 2018). All the references as well as the outgroup were retrieved from NCBI (https://www.ncbi.nlm.nih.gov/) and the Boldsystem Database (Boldsystem Database; Ratnasingham and Hebert 2007, 2013).

Parasitism rate

The parasitism rate (P) was calculated by counting the number of parasitized larvae (A) divided by the total larvae observed (B) and multiplying by 100% (P = [A/B] × 100%).

Figure 4. *Drino* (*Pelexorista*) sp. (Diptera: Tachinidae); A. Dorsal view; B. Lateral view; legs are black; C. Lacking hair around the eyes or totally bare eyes.

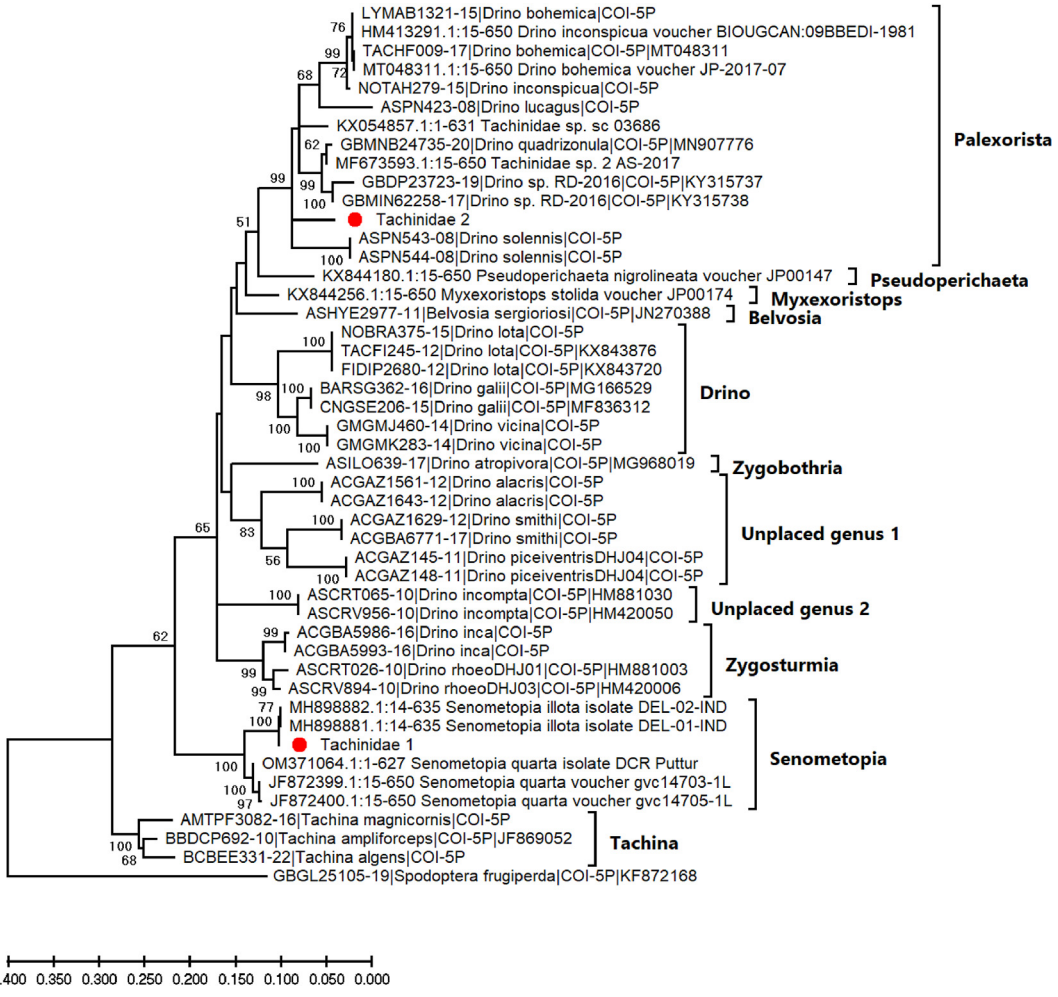

Figure 5. Dendrogram developed based on COI sequence analysis using ML method (GTR model) with 1000× bootstrap value. Red circles were samples examined; Tachinidae 1 (*S. illota*; Acc. no. OR915667) and Tachinidae 2 (*Drino* (*Palexorista*) sp.; Acc. no OR915670) were obtained from Lampung Province. Some *S. illota* and *Drino* sp. from other countries were also included. *S. frugiperda* (Acc. no. KF872168; BIN ID: AAA4532) was set as an outgroup.

Result

Observation of emerging parasitoid

A total of 1377 larvae of *S. frugiperda* in the 3rd to 5th instar were collected from four sampling locations. Maintenance was carried out until the emergence of parasitoids or until the larvae had become adults. Infected larvae with parasitoids appeared inactive, their feeding ability decreased, and there were black spots resembling scars on their bodies. The larvae would eventually die after the emergence of the parasitoid (Figure 2). Observations revealed the presence of three parasitoid families: Tachinidae, Ichneumonidae, and Braconidae.

Identification of parasitoids

The results of morphological identification revealed that within the order Diptera, family Tachinidae, there were two species identified: *Senometopia* sp. and *Drino* sp. Meanwhile, within the Hymenoptera family Ichneumonidae, they were identified as *Eriborus* sp., and within the Hymenoptera family Braconidae, they were identified as *Cheonus* sp. The phylogenetic analysis performed on the mtDNA COI sequences found that the samples were identified as *Senometopia illota* (Diptera: Tachinidae), *Drino* (*Palexorista*) sp. (Diptera: Tachinidae), Genus nr. *Eriborus* sp. (Hymenoptera: Ichneumonidae), and *Chelonus formosanus* (Hymenoptera: Braconidae). An asterisk (*) is used to indicate a new host or new distribution.

Figure 6. Genus nr. *Eriborus* sp. (Hymenoptera: Ichneumonidae); A. Dorsal view; B. Lateral view. C. Head is black (1), with scape and pedicel brown (2), occipital carina complete (3); D. lateral part of scape with blackish stripe (1), antennae dark brown with 43 segments (2); E. Face closely roughly punctate and hairy (1), Mandible brown and stout, with two teeth, apex of teeth dark brown (2), Both of palpus yellowish, labial palp three segments, maxillary palp four segments (3); F. foreleg yellowish (1), mid-leg yellow except coxae, basal par of coxa dark brown (2), hind coxa black, trochanter and trochantellus yellow, femurs to tarsi pale brown (3); G. Mesosoma black; H. Metasoma yellowish black, petiole black, its apical part brown, 2/3 of basal part of second tergite black, its apical part yellowish brown, third tergite with brown marking; I. Dorsal of mesosoma; J. Glymma on petiole present; K. Forewing; L. hindwing.

Senometopia illota (Curran, 1927) (Diptera: Tachinidae)

Diagnosis. Hypo-pleural of *S. illota* with setae and postscutellum is cylinder-shaped. Intraalar-setae behind the thoracic suture is present if only two intra-alar-setae, foremost, are reduced. The arista lacks hair or very smooth hair; the longest hairs are as long as the basal diameter of the arista. M-cu is not skewed; vein m is skewed before the margin of the wing. R5 is open or closed at the wing edge. The back side of the head has light hair; light hair below the posterior mouth is present. Gena is without hair. The calypter surface lacks hair, with only light hair present on the edge. Subapical scutellar bristles are far behind, like the apicals. Prosternum lacks hair. Eyes lacking hair or partially lacking hair. A few hairs above the vibrissae. 3rd antennal segment without a tip at the distal end. Arista's 2nd segment is shorter. Black or dark brown legs. Prealar hair is longer and stronger than notopleural. Prealar hair is more robust and more extended than notopleular hair. Eyes are densely of hair as long as 3–4× eye facets (Figure 3).

Material examined. 12 imago, Lampung Timur, Pesawaran, Pringsewu, Lampung Selatan, 21.05.2023. (P. Lestari), specimen no. PPLC 1023/Lestari-coll. PPLC.

Distribution. Afrotropical: Nigeria, South Africa, Tanzania. Oriental: China (East), India (Central, North, West), Laos, Indonesia*. Australasian & Oceanian: Australia (New South Wales, Northern Territory, Queensland, South Australia, Western Australia) (O'Hara et al. 2020)

Host. Anthela sp., *Chrysodeixis argentifera*, *Helicoperva assulta*, *Helicoverpa. Armigera, Spodoptera frugiperda*, Thysanoplusia orichalcea* (Cantrell 1986; Chaudri and Nikam 1999).

Remark. This parasitoid is widely recorded as a parasitoid of *Helicoverpa armigera*, one of the cosmopolitan pest species, which established also in Indonesia.

***Drino* (*Palexorista*)** sp. (Diptera: Tachinidae)

Diagnosis. Same like *S. illota*, hypopleural in *Drino* (*Palexorista*) sp. also has setae. The postscutellum is cylinder-shaped. Intraalar setae are present behind the thoracic suture. If only two intra-alar setae, foremost, are reduced. The arista has very smooth or lacking hair; the longest hairs are as long as the basal diameter of the arista. M-cu is not skewed; vein m is skewed before the margin of the wing. R5 is open or closed at the wing edge. Light hair on the back side of the head and below the posterior mouth is present. Gena is without hair. The calypter surface is without hair, and the edge of the calypter has light hair. Subapical scutellar bristles are far behind, like the apical. Lacks hair on the prosternum. Eyes lacking

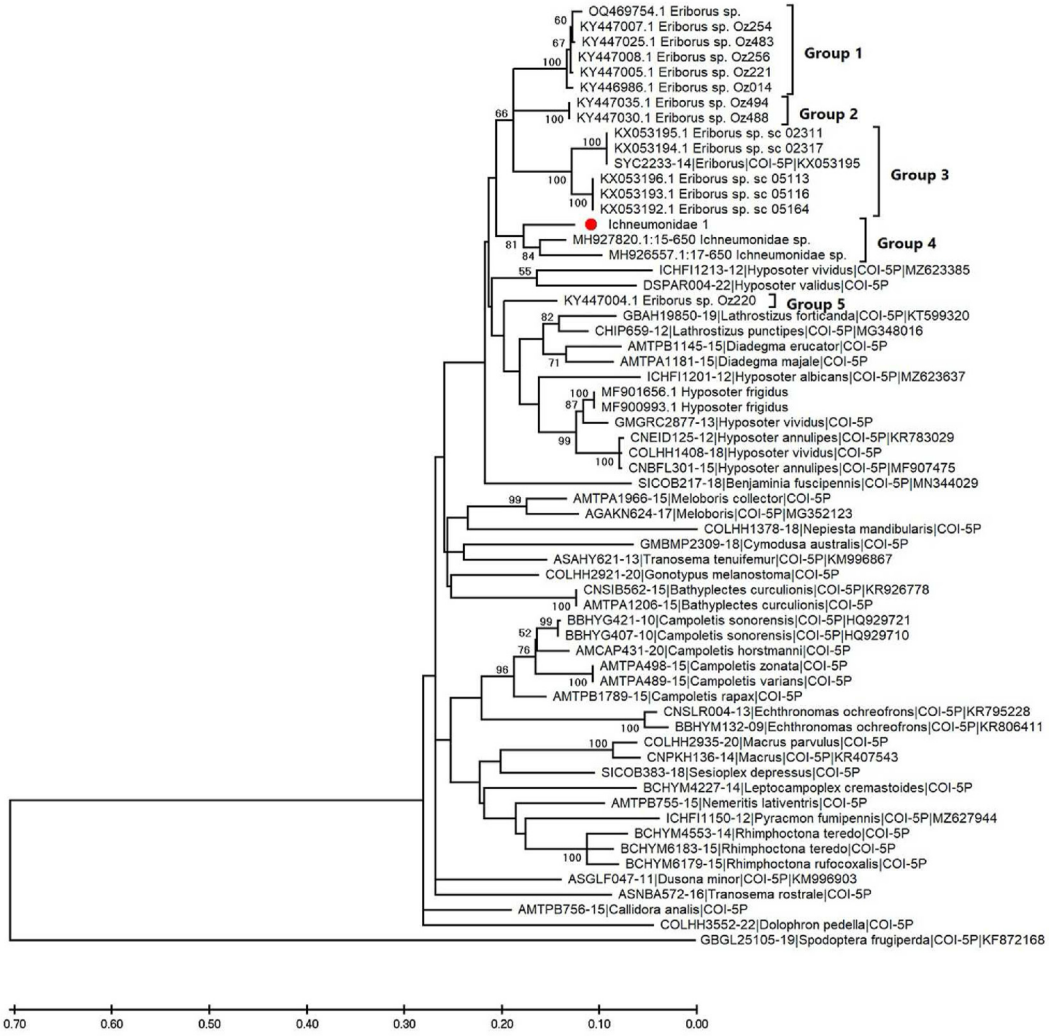

Figure 7. ML phylogenetic tree of Tribe Limneriini (Campoplegini) based on mtCOI sequence. Genus nr. *Eriborus* sp. (Acc. no. OR915668) obtained from Lampung Province was labeled red circle. Some genera of Tribe Limneriini were also included. *S. frugiperda* (Acc. no. KF872168; BIN ID: AAA4532) was set as an outgroup.

hair or partially lacking hair. A few hairs above the vibrissae. 3rd antennal segment without a tip at the distal end. Arista's 2nd segment is shorter. Legs are black or dark brown. Partially bare eyes or totally bare; femur and tibia partially black or leg completely black; setae only in the lower 1/6-2/5 of the facial ridges. Setae are short and pendulous if the setae rise on facial ridges. Discal setae on third and fourth tergite are absent. The tip palps, or scutellum, is yellow or reddish (Figure 4).

Material examined. 3 imago, Pringsewu and Lampung Selatan, 21.05.2023. (P. Lestari), specimen no. PPLC 1123/Lestari-coll. PPLC.

Distribution. Indonesia*, Thailand, Papua Guinea (Boldsystem Database; Ratnasingham and Hebert 2007, 2013).

Host. Spodoptera frugiperda (Caniço et al. 2020). Lepidoptera family Noctuidae and Pyralidae.

Remark. There are at least seven species of *Drino* (*Palexorista*) have been recorded in Indonesia such as *curvipalpis* (van der Wulp, 1893) (Java, Sulawesi), *deducens* (Walker, 1859) (Java, Sulawesi), *immersa* (Walker, 1859) (Sulawesi), *lucagus* (Walker, 1859) (Borneo), *painei* (Baranov, 1934) (Java), *solennis* (Walker 1858) (Java, Sumatra), *subanajama* (Townsend, 1927) (Sumatra), and *summaria* (Townsend, 1927) (Sumatra) (O'Hara et al. 2009). However, since the limited access to those types of materials of Indonesian Tachinids, further identification of the current species is required. At this point, the current *Drino* (*Palexorista*) sp. was molecularly distinct from Tachinids of *S. frugiperda*, *D.* (*Palexorista*) *quadrizonula* and *D.* (*Palexorista*) *zonata* also some native species such as *D.* (*Palexorista*) *lucagus*, and *D.* (*Palexorista*) *solennis* (Figure 5; labeled as Tachinidae 2). The phylogenetic analysis of COI shows that Tachinidae 1 falls into the group of *Senometopia,* and Tachinidae 2 falls into the group of *Palexorista*. Tachinidae 1 has a similarity to *S. illota*, and Tachinidae 2 has a similarity to *Drino* sp. (Figure 5).

Genus nr. *Eriborus* sp. (Hymenoptera: Ichneumonidae)

Diagnosis. Identification was based on body and leg color, as well as wing venation. The body color is predominantly black or reddish-black, with the forewing having an open areolate structure and vein 3Rs-m absent. The M section on the forewing is as long as 2Rs-m or shorter. The ovipositor does not sweep up toward the peak. The head is black, while the antennae are dark brown and consist of 43 segments with a yellowish scape and a black patch on the lateral side of the scape. The face is hairy, and the mandibles are brown with dark brown tips on the teeth. The labial palps and maxillary palps are yellowish, with three segments on the labial palps and four segments on the maxillary palps. The mesosoma is black, and the metasoma is yellowish-black (Figure 6).

Material examined. 18 imago, Lampung Timur, Pesawaran, Pringsewu, Lampung Selatan, 21.05.2023. (P. Lestari), specimen no. PPLC 1223/Lestari-coll. PPLC.

Distribution. Indonesia (Lampung* and West Sumatra) and Bangladesh (Boldsystem Database; Ratnasingham and Hebert 2007, 2013).

*Host. Spodoptera frugiperda**

Remark. Morphologically, the characteristics resembling *Eriborus* and having open areolet and short ovipositor, a combination characters that are rare in the genus group however genetically the current genus was confused by at least five distinct groups of the *Eriborus* genus (Figure 7). It is suggested that the *Eriborus* sensu lato was consist with several distinct genera. Therefore, this study considered the sequences group 4 as *Ichneumonidae* Genus nr. *Eriborus* sp.

Chelonus formosanus (Sonan, 1932) (Hymenoptera: Braconidae)

Diagnosis. Imago of *C. formosanus*, both males and females have the same body color. Generally, the body of this parasitoid is black. The foreleg and midleg are yellowish-orange in color, with black coxa and trochanters. The tibia of the hind leg is yellowish-white.

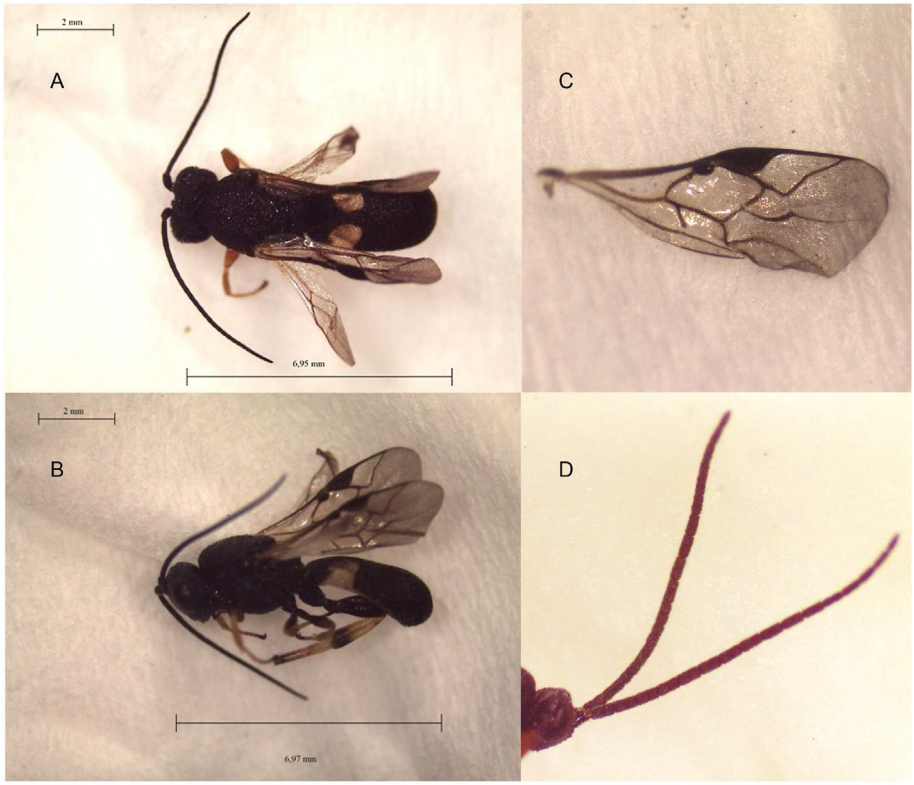

Figure 8. *C. formosanus* (Hymenoptera: Braconidae); A. Dorsal view; B. Lateral view; C Forewing; D. Antennae with 24 segments.

Wings are membranous, with dark brown pterostigma and parastigma. Frons and Clypeus compact setose. Vertex is compact, setose, and rough-textured. Head with setae white in color. The segment antennae consist of 24–26 segments, with the flagellum comprising 22–23 segments in the female. Whereas in males, the flagellum consists of 26 segments. The basal flagellum is thickened and stronger. The apical flagellum is clubbed. Mesosoma was wrinkled and rough; rough areolate scutellum; Propodeum reticulate with a strong lateroapical tubercle. The metasoma has a pair of yellowish spots on the lateral side. The integument of the metasoma is convex (Figure 8).

Material examined. 1 imago, Lampung Timur, 21.05.2023. (P. Lestari), specimen no. PPLC 1323/Lestari-coll. PPLC.

Distribution. Indonesia*, China, India, Bhutan, America (North America, Texas, United States, and Travis County), and Honduras (Liu et al. 2022; Gupta et al. 2020; Dorji et al. 2022)

Host. Lepidoptera: Cosmopterigidae, egg-larval Noctuidae (*S. frugiperda, S. exigua, S. litura, Helicoverpa armigera,* and *Mythimna loreyi*) (Gupta et al. 2020; Liu et al. 2022; Rai 1974; Yuan et al. 2022)

Remark. The phylogenetic analysis performed on the mtDNA COI sequences found that the samples of Braconidae 1 was identified as *C. formosanus* and clustered into the same clade as *C. bifoveolatus* (Figure 9). There is clear evidence that the barcode sequences of *C. formosanus* were identical to the *C. bifoveolatus* ex *S. frugiperda* from (Shen et al. 2023; Agboyi et al. 2020) suggests possibility they are conspecific. However, the *C. bifoveolatus* characteristics described by Shen et al. 2023 were actually more closely related to *C. formosanus* instead of the *C. bifoveolatus* described by Szepligeti (1914) as has also been acknowledged in their description. Hence, we identified the current specimen as *C. formosanus* instead of *C. bifoveolatus*.

Parasitism rate

There was an increase in the parasitism rate of *S. frugiperda* in Lampung Province from 1.2–3.14% in 2021 to 3.17–4.81% in 2022 (Figure 10). Among the regions, Lampung Selatan has the highest parasitism rate. Notably, the attack rate that occurred in Lampung Selatan was 26.5%, lower compared to Lampung Timur, which reached 79.12% (Lestari et al. 2020). Across all sampling locations, *S. illota* and Genus nr. *Eriborus* sp. were the most frequently found parasitoids (Figure 11). Genus nr. *Eriborus* sp. showed a substantial increase in parasitization, indicating its potential to suppress the *S. frugiperda* population.

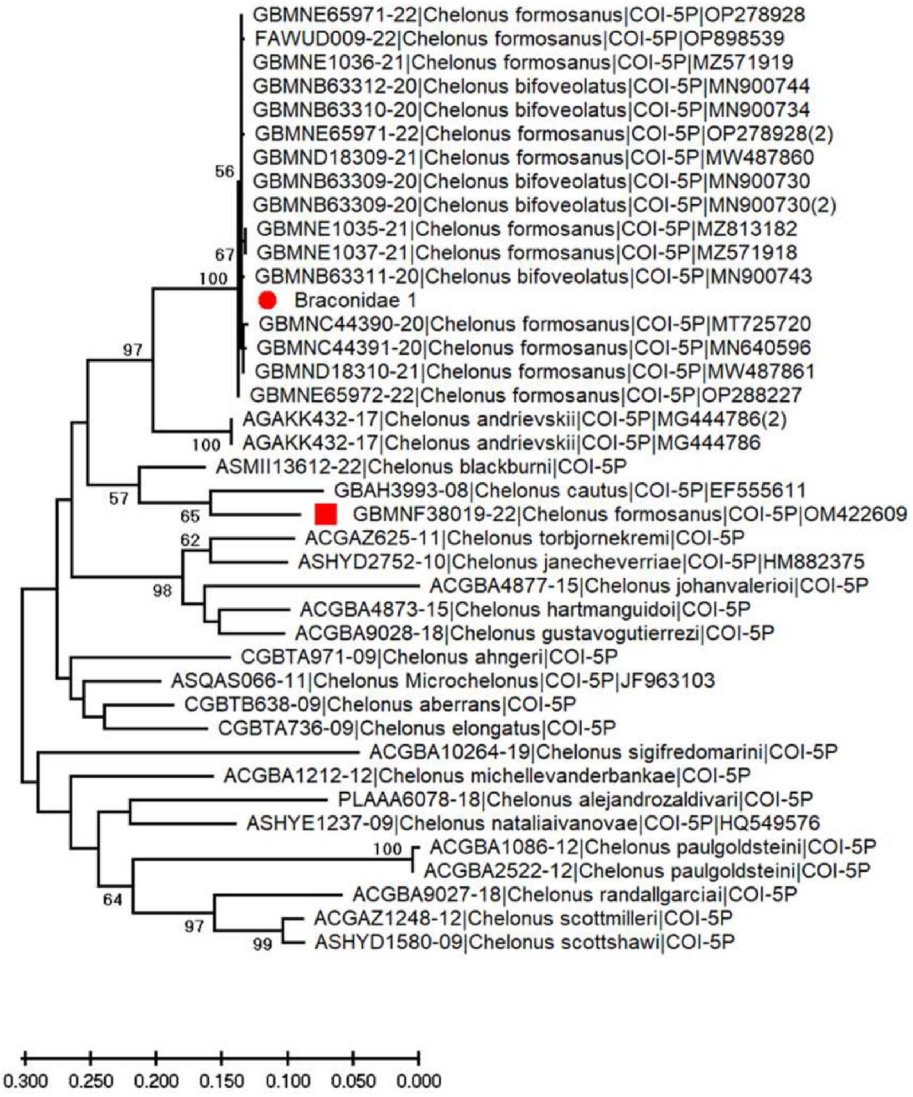

Figure 9. Unrooted phylogenetic tree-based mtCOI analysis using Maximum Likelihood method (General Time Reversible model) with 1000× bootstrap value. The red circle was the sample examined, *C. formosanus* (Acc. no OR915669) obtained from Lampung Province. Some *Chelonus* from other countries were also included.

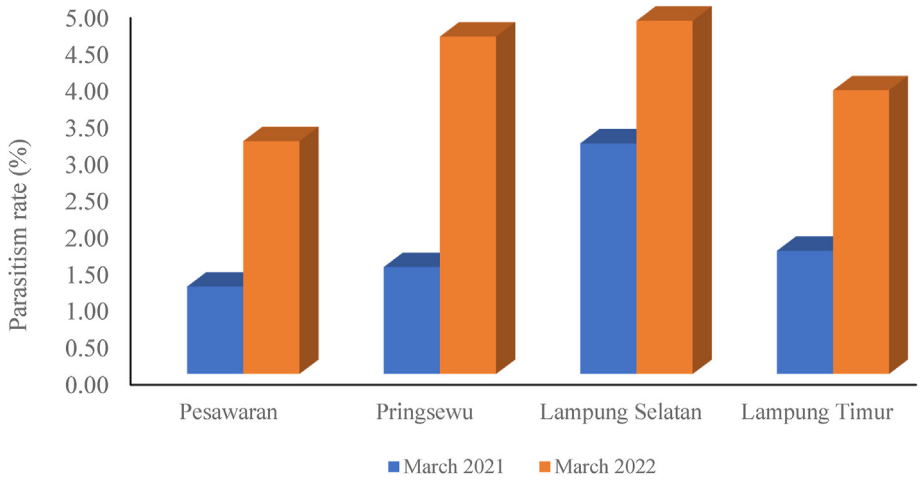

Figure 10. The parasitism rate of parasitoids on *S. frugiperda* larvae in Lampung Province has observed an increase recently.

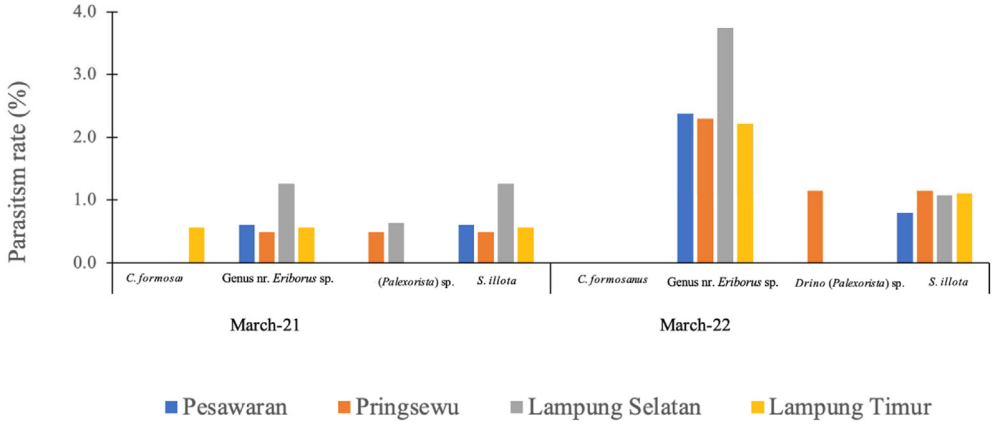

Figure 11. The parasitism rate of each parasitoid increased in 2022, with the Genus nr. *Eriborus* sp. shows the highest parasitization in all districts, followed by *S. illota.*

Table 1. The same genus of parasitoids on *H. armigera* were parasitized *S. frugiperda.*

Species	Order: Family	Host	Country	References
Genus *Campoletis*				
Campoletis chloridae	Hymenoptera: Ichneumonidae	*H. armigera*	India	Pawar et al. (1989)
Campoletis chloridae (Vierech)	Hymenoptera: Ichneumonidae	*S. frugiperda*	Barbados	Alam (1979)
Genus *Bracon*				
Bracon hebetor	Hymenoptera: Braconidae	*H. armigera*	Israel	Bar et al. (1979)
Bracon sp.	Hymenoptera: Braconidae	*S. frugiperda*	Ghana	Koffi et al. (2020)
Genus *Hyposoter*				
Hyposoter didymator	Hymenoptera: Ichneumonidae	*H. armigera*	Spain	Hatem et al. (2016)
Hyposoter sp.	Hymenoptera: Ichneumonidae	*S. frugiperda*	France	Dorémus et al. (2013)
Genus Archytas				
Archytas marmoratus (Townsend)	Diptera: Tachinidae	*H. armigera*	Brazil	Guerra et al. (2014)
Archytas marmoratus (Townsend)	Diptera: Tachinidae	*S. frugiperda*	Wide-spread all continent	Gross and Young (1984)
Genus *Eucelatoria*				
Eucelatoria bryani Sabrosky	Diptera: Tachinidae	*H. armigera*	India	Mani and Krishnamoorthy (1983)
Eucelatoria bryani Sabrosky	Diptera: Tachinidae	*S. frugiperda*	Brazil	Sabrosky and Curtis (1981)

Discussion

The outbreak of *S. frugiperda* in the Lampung Province has been reported to have occurred since the pest invasion in 2019 (Trisyono et al. 2019; Lestari et al. 2020). Such outbreaks occur when an invasive species enters an area devoid of its natural enemies or when the native natural enemies have not yet adapted to counter the invasive species. Although there is no definitive evidence

regarding the spread of *S. frugiperda* to Indonesia, there is a strong suspicion that it entered the country from regions such as America, Africa, India, Myanmar, and the Philippines before reaching the West Sumatra region, Indonesia (Nonci et al. 2019).

In this study, four parasitoids were identified: *S. Illota* (Diptera: Tachinidae), *Genus nr. Eriborus* sp. (Hymenoptera: Ichneumonidae), *Drino* (*Palexorista*) sp. (Diptera: Tachinidae), and *C. formosanus* (Hymenoptera: Braconidae). While *S. illota* and Genus nr. *Eriborus* sp. are native parasitoids in Indonesia and have never been reported as parasitoids of *S. frugiperda,* globally. Some species are cosmopolitant species, such as *S. illota* (Diptera: Tachinidae) and *C. formosanus* (Hymenoptera: Braconidae), while *Genus nr. Eriborus* sp. (Hymenoptera: Ichneumonidae) and *Drino* (*Palexorista*) sp. (Diptera: Tachinidae) are strongly suggested as native parasitoids in Southeast Asia since their genetic structures were distinct from the recorded species (Boldsystem Database; Ratnasingham and Hebert 2007, 2013).

There have been reports of various parasitoids from the same genera in S. frugiperda-affected nations. Two species of *Chelonus* were reported as parasitoids of *S. frugiperda* in Benin and Ghana (Agboyi et al. 2020; Tepa-Yotto et al. 2021), a finding also observed in India (Gupta et al. 2020). In Africa, the Tachinid fly *D.* (*Palexorista*) *zonata* has been reported as a larval parasitoid of *S. frugiperda* (Sisay et al. 2018). Additionally, *D.* (*Palexoista*) *quadrizonula* Thomson (Diptera: Tachinidae) has also been reported as a larval parasitoid of *S. frugiperda* in Mozambique (Caniço et al. 2020). On the other hand, the current study also found *S. illota* which is known well as parasitoid *Helicoverpa armigera* (Chaudri and Nikam 1999) is able to

Table 2. The same genus of parasitoid on *S. litura* and *S. exigua* were parasitized *S. frugiperda*.

Species	Order: Family	Host	Country	References
Genus: *Cotesia* syn *Apanteles*				
Apanteles chilonis	Hymenoptera: Braconidae	*S. litura*	Indonesia	Chu (1979)
Apanteles marginiventris	Hymenoptera: Braconidae	*S. frugiperda*	America	Ashley (1979)
Cotesia (Apanteles) glomeratus (Linnaeus)	Hymenoptera: Braconidae	*S. frugiperda*	Barbados	Alam (1979)
Cotesia (Apanteles) marginiventris (Cresson)	Hymenoptera: Braconidae	*S. frugiperda*	Mexico	Marsh 1978
Genus *Brachymeria*				
Brachymeria exccarillata	Hymenoptera: Chalcididae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Brachymeria ovata (Say)	Hymenoptera: Chalcididae	*S. frugiperda*	Nepal	Bhusal and Chapagain (2020)
Genus *Charops*				
Charops brachypetrum	Hymenoptera: Ichneumonidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Charops ater Szépligeti	Hymenoptera: Ichneumonidae	*S. frugiperda*	Kenya, Tanzania	Abang et al. (2021)
Charops sp.	Hymenoptera: Ichneumonidae	*S. frugiperda*	Benin, Ghana, Mozambique	Agboyi et al. (2020)
Genus *Chelonus*				
Chelonus blackburni	Hymenoptera: Braconidae	*S. litura*	Indonesia	Rao et al. (1979)
Chelonus formosanus (Sonan)	Hymenoptera: Braconidae	*S. frugiperda*	Barbados, India	Gupta et al. (2020)
Chelonus toxanus	Hymenoptera: Braconidae	*S. frugiperda*	Florida	Ashley (1979)
Genus *Diadegma*				
Diadegma semiclausum	Hymenoptera: Ichneumonidae	*S. exigua*	Indonesia	Shepard and Barrion (1998)
Diadegma sp.	Hymenoptera: Ichneumonidae	*S. frugiperda*	Argentina	Virla et al. (1999)
Genus *Eriborus*				
Eriborus argenteopilosus	Hymenoptera: Ichneumonidae	*S. exigua*	Indonesia	Shepard and Barrion (1998)
Eriborus sp.	Hymenoptera: Ichneumonidae	*S. frugiperda*	India	Sharanabasappa et al. (2019)
Genus *Euplectrus*				
Euplectrus sp.	Hymenoptera: Eulophidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Euplectrus comstockii (Howard)	Hymenoptera: Eulophidae	*S. frugiperda*	US	Luginbill (1928)
Euplectrus platyhypenae	Hymenoptera: Eulophidae	*S. frugiperda*	US	Hay-Roe et al. (2013)
Genus *Glyptapanteles*				
Glyptapanteles sp.	Hymenoptera: Braconidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Glyptapanteles creatonoti (Viereck)	Hymenoptera: Braconidae	*S. frugiperda*	India	Shylesha et al. (2018)
Genus *Metopius*				
Metopius rufus javanus	Hymenoptera: Ichneumonidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Metopius rufus (Ashmead)	Hymenoptera: Ichneumonidae	*S. frugipreda*	India	Abang et al. (2021)
Genus *Microplitis*				
Microplitis similis	Hymenoptera: Braconidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Microplitis manilae	Hymenoptera: Braconidae	*S. litura*	Indonesia	Syahidah et al. (2020)
Microplitis sp.	Hymenoptera: Braconidae	*S. exigua*	Indonesia	Shepard and Barrion (1998)
Microplitis sp.	Hymenoptera: Braconidae	*s. frugiperda*	Indonesia	Sari et al. (2023), Tarigan et al. (2023)
Microplitis manilae (Ashmead)	Hymenoptera: Braconidae	*S. frugiperda*	India,	Gupta (2013)
Microplitis palipides	Hymenoptera: Braconidae	*S. frugiperda*	China	Ju et al. (2021)
Genus *Rogas*				
Rogas sp.	Hymenoptera: Braconidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Aleiodes sp. Syn: *Rogas* sp.	Hymenoptera: Braconidae	*S. frugiperda*	Brazil	Shimbori et al. (2023)
Genus *Temelucha*				
Temelucha bigurrula	Hymenoptera: Ichneumonidae	*S. litura*	Indonesia	Chu (1979)
Temelucha sp.	Hymenoptera: Ichneumonidae	*S. frugiperda*	North Indian	Sagar et al. (2022)
Tachinidae				
Tachinidae (unidentified)	Diptera: Tachinidae	*S. litura*	Indonesia	Shepard and Barrion (1998)
Tachinidae sp.	Diptera: Tachinidae	*S. frugiperda*	Georgia	Riggin et al. (1993)

parasitize *S. frugiperda*. It indicates that *S. illota* has the potential to inhabit other Noctuidae as their host as well as recorded from other parasitoids of *H. armigera* (Table 1). Various genera of *Spodoptera* larvae parasitoids in Indonesia were also reported to parasitize *S. frugiperda* larvae in several countries (Table 2). Therefore, the discovery of *S. illota*, *Genus nr. Eriborus* sp., and *Drino* (*Palexorista*) sp. parasitizing *S. frugiperda* can be valuable information for potential biological control agents of *S. frugiperda* with parasitism rate ranges from 3.17 to 4.81% (Figures 10 and 11).

Parasitism of unidentified species of *Eriborus* on *S. frugiperda* has been reported in Sumatra Barat (Sari et al. 2023), Nusa Tenggara Barat (Supeno et al. 2021), and India (Sharanabasappa et al. 2019); however, since the lack the morphological characteristics described, it is unclear whether they are the same species with the current specimen. Even though the current Ichneumonidae wasp ex. *S. frugiperda* bears morphological similarities to *Eriborus*, this genus was genetically separated from *Eriborus*. Therefore, further investigation is needed to clarify the status of the current genus *Eriborus*.

In Indonesia, there is no specific report of *C. formosanus*. However, the parasitization of *Chelonus* sp. in Lepidoptera larvae has been extensively described. *Chelonus* is known to parasitize several species of *Spodoptera* (Jones 1985). The *C. formosanus* found in this study is genetically identical to the one reported in India. *Chelonus* is the largest genus in the subfamily Cheloninae (Hymenoptera: Braconidae), and its endoparasitoid lays its eggs in the larvae (Shen et al. 2023). *Chelonus* is found in the Americas and Africa (Otim et al. 2021). *C. insularis* parasitizes *S. frugiperda* on West and South African corn, reaching up to 91% parasitism (Ngangambe and Mwatawala 2020). The results of phylogenetic analysis indicate that the *C. formosanus* found in this study bears similarity to both *C. formosanus* and *C. bifoveolatus*. However, observations of the morphology of the female sample were found to lean more towards *C. formosanus,* as reported (Gupta et al. 2020), with a body length size ranging from 6.95 to 6.97 mm and 24 segments of the antenna. Meanwhile, the female *C. bifoveolatus* has a smaller body size of 5.5 mm with 27 antenna segments and distinct pigmentation on the hind foot (Szepligeti 1914).

Conclusion

Four parasitoids of *S. frugiperda* were found in Indonesia: *S. illota,* Genus nr. *Eriborus* sp., *C. formosanus*, and *Drino* (*Palexorista*) sp. Two species i.e. *S. illota* and Genus nr. *Eriborus* sp. are newly recorded parasitoids of *S. frugiperda* worldwide. The taxonomy of the genera *Eriborus* and *Drino* required to be revised extensively.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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