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Research Article

First records of egg parasitoids of *Halyomorpha halys* (Stål, 1855) (Hemiptera, Pentatomidae) in Hungary

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Abstract

The brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål, 1855) (Hemiptera: Pentatomidae), is a highly polyphagous pest native to South Korea, North Korea, Japan, Taiwan, and China, which has become invasive in the Americas and Europe. *H. halys* has spread rapidly in invaded areas, causing crop damage and nuisance problems due to large overwintering populations. In recent years, several studies have investigated parasitoids of *H. halys* within its invaded regions. These studies recovered the coevolved parasitoids *Trissolcus japonicus* and *Tr. mitsukurii* in the regions. The present research surveyed parasitoids of *H. halys* in Hungary and cities in Southeastern Europe (Oradea, Novi Sad, and Sofia). Several native European parasitoids belonging to the families Encyrtidae, Eupelmidae, and Scelionidae were recorded parasitizing eggs of *H. halys* under field conditions, with the most common species being *Anastatus bifasciatus*. In addition to native parasitoids, *Tr. japonicus* and *Tr. mitsukurii* were recorded for the first time in Hungary and Oradea, respectively. Further studies are needed to explore the relationship between native and exotic species and to evaluate their impacts, which will help identify the optimal approach for utilizing these parasitoid species in managing *H. halys*.

Key words: *Anastatus bifasciatus*, *Halyomorpha halys*, *Trissolcus japonicus*, *Trissolcus mitsukurii*

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Introduction

The brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål, 1855) (Hemiptera: Pentatomidae), is native to South Korea, North Korea, Japan, Taiwan, and China (Zhu et al. 2012). In 2007, *H. halys* was first reported in Europe from Zurich, Switzerland (Wermelinger et al. 2008). The pest has since been recorded in many parts of Europe, North America, and South America, specifically Argentina and Chile (EPPO 2025). In Hungary, *H. halys* was first reported in 2013 from the Buda Arboretum, Budapest (Vétek et al. 2014). In late summer 2016, *H. halys* was reported infesting vegetables. Investigation revealed that 94% of seeds in dry bean pods and 100% of the sampled green hot pepper fruits were damaged by *H. halys* (Vétek and Korányi 2017). By 2018, *H. halys* had spread widely across Hungary, including almost all districts of Budapest (Vétek et al. 2018). Globally, *H. halys* has caused significant economic losses, including \$37 million (USD) in damage to apple production in the mid-Atlantic region of the United States (Leskey and Nielsen

† Deceased.

2018; United States Apple Association 2010; Regmi et al. 2024) and €500 million in financial support allocated to Italian fruit farmers in 2019 (Commission Implementing Regulation [EU] 2020/465). It is estimated that the establishment of *H. halys* in New Zealand could reduce GDP and horticultural export value by several billion NZD by 2038 (Clough 2017). Additionally, *H. halys* not only damages crops but also causes significant public nuisance through its large overwintering aggregations (Wermelinger et al. 2008).

In its native range, several egg parasitoids attack *H. halys* eggs, including species from the genera *Trissolcus* Ashmead, *Telenomus* Haliday (Hymenoptera: Scelionidae), *Ooencyrtus* Ashmead (Hymenoptera: Encyrtidae), and *Anastatus* Motschoulsky (Hymenoptera: Eupelmidae) (Yang et al. 2009; Zhang et al. 2017). In China, *Trissolcus japonicus* (Ashmead) is the dominant parasitoid species, with parasitism rates ranging from 50% to 90%, whereas in Japan, *Tr. mitsukurii* (Ashmead) is the primary parasitoid (Yang et al. 2009; Lee et al. 2013; Zhang et al. 2017). Several studies in North America and Europe have focused on identifying parasitoids of *H. halys* for potential use in the development of sustainable long-term management practices against this invasive pest (Jones et al. 2014; Haye et al. 2015; Dieckhoff et al. 2017; Costi et al. 2019; Moraglio et al. 2020; Zapponi et al. 2020; Rot et al. 2021; Andreadis et al. 2021). These surveys indicate that three main families of hymenopteran parasitoids are capable of parasitizing *H. halys* eggs in invaded regions: Scelionidae (*Telenomus*, *Trissolcus*, and *Hadronotus* Förster, reported as *Gryon* Haliday), Eupelmidae (*Anastatus*), and Encyrtidae (*Ooencyrtus*). Among these, *Anastatus bifasciatus* (Geoffroy) is the most widespread and promising native parasitoid in Europe capable of attacking *H. halys* eggs (Haye et al. 2015; Roversi et al. 2016; Abram et al. 2017; Costi et al. 2019). However, a 3-year study conducted in four orchards in Switzerland and Italy assessed biocontrol of *H. halys* with augmentative releases of *An. bifasciatus* and found that an average parasitism rate of 6% was insufficient for effective pest management (Stahl et al. 2019a). In addition to native parasitoid species, new avenues for biological control of *H. halys* in Europe now exist because of the unintentional establishment of exotic parasitoids such as *Tr. japonicus* in Switzerland in 2017 (Stahl et al. 2019b) and Northern Italy in 2018 (Sabbatini Peverieri et al. 2018), as well as *Tr. mitsukurii* in Northeastern Italy in 2016 (Scaccini et al. 2020), Western Slovenia in 2020 (Rot et al. 2021), Germany in 2021 (Dieckhoff et al. 2021), and in 2024 in Southwestern France (Martel et al. 2024), and Serbia (Konjević et al. 2024). The establishment of *Tr. japonicus* in Europe could reduce the population densities of *H. halys*. However, *Tr. japonicus* may pose a risk to native, beneficial Pentatomidae (Haye et al. 2024). A classical biological control program targeting *H. halys* was initiated in Italy, where *T. japonicus* (from a laboratory-reared colony originally collected in Beijing, China, and supplied by USDA-ARS BIIRU, Newark, DE, USA) was introduced and released under authorization (authorization number DG/DISR/DISR05/0013647-19/04/2018) by the Italian Ministry of Agriculture. Costi et al. (2022) investigated the potential for multiparasitism of *H. halys* eggs by *Tr. mitsukurii* and *Tr. japonicus* and reported that both species were able to parasitize *H. halys* eggs previously parasitized by the other species. Since the rapid spread of *H. halys* and its threat to crop production and biodiversity, studies on life history, ethology, and management have increased in invaded regions. Various techniques for obtaining *H. halys* egg parasitoids have been applied effectively, including the utilization of sentinel eggs, the collection of wild egg masses (Jones et al. 2014; Haye et al. 2015; Costi et al. 2019), and the exposure of naturally laid eggs within sleeve cages (Costi et al. 2019). However, Jones et al. (2014) reported that the use of sentinel eggs underestimates actual parasitism rates and provides inaccurate estimates of parasitoid community composition, and that host plant–associated cues present in wild egg masses may affect parasitoids. In this study, we investigated the occurrence of parasitoids on *H. halys* eggs in Hungary to evaluate their potential as biological control agents.

Materials and methods

Surveys of parasitoids associated with *H. halys* eggs were conducted in multiple regions across Hungary using two methods: assessing parasitism in naturally laid eggs inside cages and collecting wild egg masses. Naturally laid eggs in cages were surveyed in the Buda Arboretum (Budapest) in 2021 and in apple orchards in Budapest (Soroksár) in 2022. Wild egg masses were collected from various host plants and locations across Hungary and from cities in neighboring countries between 2020 and 2022. The collection sites of wild egg masses in 2020 and 2022 are listed in Table 1.

Table 1. Details of wild egg masses of *Halyomorpha halys* collected in 2020, 2021, and 2022, along with the associated parasitoids that emerged (nd = no data).

Location	Year	Habitat	Egg masses	Eggs	Hatched nymphs	Unhatched eggs	Parasitized egg mass	% Hatched	% Unhatched	% Parasitized	Parasitoids emerged
Budapest	2020	Urban Park, sidewalk	3	nd	nd	nd	nd	nd	nd	nd	9
Szigetbecse	2020	Agricultural field	1	nd	nd	nd	nd	nd	nd	nd	23
Budapest (Soroksár)	2021	Orchard Agricultural field	11	288	204	71	1	70.83	24.65	4.51	13
Budapest	2021	Urban Park, sidewalk	20	475	213	219	4	44.84	46.11	11.36	54
Érd	2021	Orchard	16	383	325	58	0	84.86	15.14	0.00	0
Oradea	2021	Urban Park, sidewalk	17	395	113	170	10	28.61	43.04	28.35	112
Sofia	2021	Urban Park, sidewalk	2	33	0	33	1	0.00	78.79	21.21	7
Novi Sad	2021	Urban Park, sidewalk	4	107	28	79	1	26.17	58.88	14.95	16
Szeged	2022	Urban sidewalk	45	1076	770	306	9	71.56	21.56	6.88	74
Budapest	2022	Urban Park, sidewalk	38	859	156	703	13	18.16	69.38	12.46	107
Tarcal	2022	Urban sidewalk	1	26	24	2	0	92.31	7.69	0.00	0
Budapest (Soroksár)	2022	Orchard, Agricultural field	6	110	29	81	1	26.36	59.09	14.55	16

Naturally laid eggs in cages

Overwintering populations of *H. halys* adults were collected from several locations in Budapest during the autumns of 2020 and 2021, primarily from sunshades at restaurants. Field-collected *H. halys* adults were kept in a climate chamber for hibernation under controlled environmental conditions: temperature 4 ± 0.9 °C, relative humidity (RH) 70 ± 10%, and 8:16 h light:dark (L:D) photoperiod. Hibernating adults were transferred from the climate chamber to an outdoor environment (natural conditions), sheltered under a roof to protect them from precipitation, and maintained in Bug Dorms (4S2260 Insect Rearing Cage; W24.5 × D24.5 × H63.0 cm, Australian Entomological Supplies Pty Ltd) during spring to regain activity. Food items, including apple slices, carrots, peanuts, and sunflower seeds, as well as water-soaked cotton, were provided to adult *H. halys* twice a week.

In 2021, the experiment using eggs naturally laid in cages was conducted from April to September. The cages used in this experiment (100 × 30 × 30 cm, mesh size 3 × 3 mm), following Costi et al. (2019) (Fig. 1), were tied to selected twigs of host plants, and three pairs of adult *H. halys* were introduced into each cage. The mesh size of the net was sufficiently large to permit the entry of parasitoids while preventing the escape of adult *H. halys*. Adults inside cages were monitored and provided with a diet of beans, apple slices, and carrots. Fresh food was provided twice a week. Dead *H. halys* were replaced with new adults as needed. This arrangement facilitated mating and egg laying, allowing the eggs to be exposed to natural parasitism until they were ready to hatch. All egg masses laid in cages were collected and placed in separate petri dishes (15 × 100 mm) in the laboratory. Emerging *H. halys* nymphs were removed, and the remaining unhatched eggs were kept at room conditions for parasitoid emergence. Experimental cages were set up in multiple locations within the Buda Arboretum on the Hungarian University of Agriculture and Life Sciences, Budapest campus (47.4822°N, 19.0402°E). The locations focused on selected host plant species (*Syringa* × *hyacinthiflora* Lemoine, *Crataegomespilus dardaii* Simon-Louis, *Crataegus pinnatifida* Bunge, *Forsythia* × *intermedia* Zabel 'Spring glory', *Acer campestre* Linnaeus 'Zenta', *Ac. campestre* 'Red shine', *Carpinus betulus* Lindman 'Purpurea', *Fraxinus pennsylvanica* Marshall, *Malus* 'Eleyi', *Malus* 'Winter

Figure 1. A mesh cage on maple used to enclose adult *Halyomorpha halys*.

Gold', *Tilia tomentosa* Mill 'Wagner Janos', *Morus nigra* Linnaeus 'Nana', *Malus* 'Aldemahensis', *Prunus cerasifera* Ehrh., *Prunus serrulata* Lindley var. *hupehensis*, *Acer platanoides* Linnaeus, *Acer pseudoplatanus* Linnaeus, and *Sorbus aria* Linnaeus 'Lutescens'). In 2022, the experiment was conducted in an apple orchard at the Hungarian University of Agriculture and Life Sciences Research and Experimental Farm in Budapest (Soroksár) (47.3966°N, 19.1418°E) from May to September. No insecticide treatments were applied in the orchard during the study year.

Wild egg masses

From 2020 to 2022, a comprehensive search for wild egg masses of *H. halys* was conducted from June to September across various locations in Hungary, along with a one-time collection in a few cities in Southeast Europe, including Novi Sad (Serbia), Sofia (Bulgaria), and Oradea (Romania) (Fig. 2). The survey was done with visual inspections of plants frequently utilized by *H. halys*, such as *Ailanthus altissima* Miller (Simaroubaceae), Sapindaceae, *Acer negundo* Linnaeus, *Ac. pseudoplatanus* Linnaeus, *Ac. campestre* Linnaeus, *Fraxinus pennsylvanica* Marshall (Oleaceae), *Populus alba* Linnaeus (Salicaceae), and *Celtis occidentalis* Linnaeus (Cannabaceae). Details on host plants from which parasitized *H. halys* egg masses were collected in Hungary in 2020, 2021, and 2022 are provided in Table 2.

Surveys were conducted in Budapest and Szigetbecse in 2020, in Budapest and Érd in 2021, and in Budapest, Tarcal, and Szeged in 2022. In Budapest, wild *H. halys* egg masses were collected from various locations. The habitat types where wild egg masses were collected were categorized as urban sidewalk, urban park, and agricultural areas. In Budapest, egg masses were collected from both urban and agricultural areas, categorized as Budapest and Budapest (Soroksár), respectively. Details of the collection sites for wild egg masses are provided in Table 1 and Fig. 2.

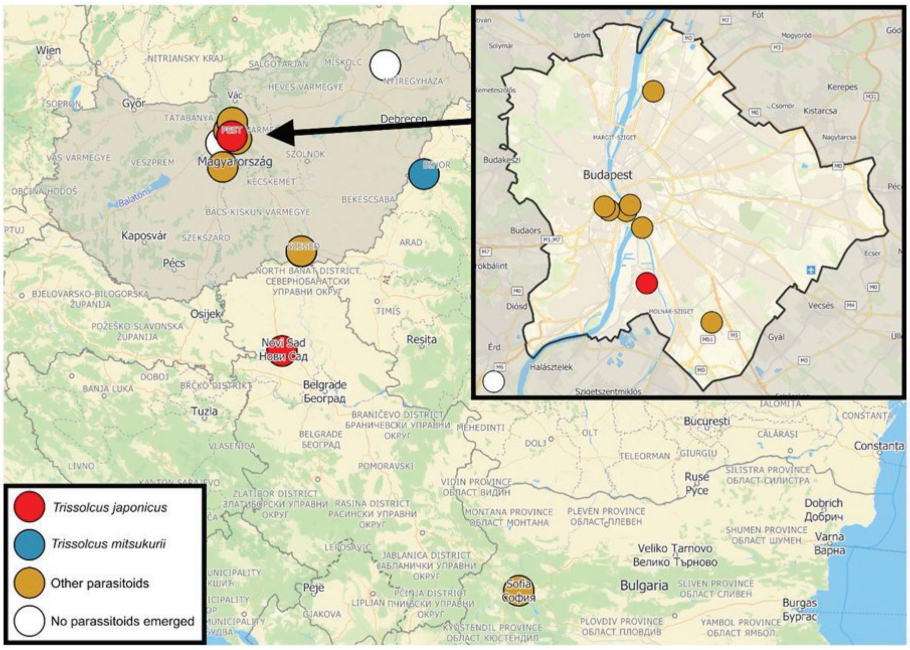

Figure 2. Wild *Halyomorpha halys* egg mass collection sites and identities of parasitoids reared from *H. halys* eggs collected in Hungary and neighboring countries (Romania, Serbia, and Bulgaria) between 2020 and 2022.

Table 2. Host plants from which parasitized egg masses of *Halyomorpha halys* were collected in Hungary in 2020, 2021, and 2022.

Host plant	Total egg masses collected	Parasitized egg masses
Ailanthus altissima	46	12
Acer pseudoplatanus	13	1
Fraxinus pennsylvanica	14	4
Populus alba	6	2
Celtis sp.	1	0
Acer negundo	10	4
Acer campestre	4	2
Allium porrum	1	1

Collected egg masses were individually placed in labeled petri dishes and maintained under laboratory conditions (~23 °C) at the Department of Entomology, Hungarian University of Agriculture and Life Sciences, to monitor the emergence of *H. halys* nymphs or adult parasitoids. The number of hatched nymphs, emerged parasitoids, and unhatched eggs was recorded for each egg mass. Emerged parasitoids were preserved in vials containing 90% ethanol, and each vial was labeled for subsequent species identification. Identification of wild *H. halys* egg masses was carried out in accordance with the criteria described by Kobayashi (1967).

Parasitoid identification

Once emerged, parasitoids were transferred into 1.5 mL microcentrifuge tubes (Eppendorf SE, Germany) containing 90% ethanol to ensure preservation prior to identification. Morphological identifications were performed under a stereomicroscope using taxonomic keys. For Eupelmidae, reference was made to Askew and Nieves-Aldrey (2004) and Peng et al. (2020). Specimens of the genus *Trissolcus* Ashmead were identified using identification keys, diagnostic characters, and illustrations in Talamas et al. (2017), Tortorici et al. (2019), and Moraglio et al. (2021). For *Telenomus*, Tortorici et al. (2024) was used. All specimens examined for morphological analysis have been deposited as vouchers in the entomological collections of the Department of Agricultural, Forest and Food Sciences (DISAFA), University of Torino (Italy).

Evaluation of parasitoid efficacy

The assessment of parasitoid efficacy was conducted following the methodology outlined by Bin and Vinson (1991) and Rot et al. (2021). The impact of the parasitoid, represented by the parasitism rate, was assessed for each location and year by calculating the number of parasitized eggs in relation to the total number of eggs collected from the field (Table 1).

Results

Naturally laid eggs in cages

In 2021, 85 egg masses were collected in the Buda Arboretum, and no parasitism was observed. In 2022, the experiment was conducted in an apple orchard at Budapest (Soroksár), where a total of 47 egg masses were collected. Only three

Table 3. Details of *Halyomorpha halys* egg masses laid in mesh cages with associated parasitoids that emerged from eggs (Buda Arboretum, 2021, and apple orchard, 2022).

Year	Egg masses	Eggs	Hatched nymphs	Unhatched eggs	Parasitized egg masses	% Hatched	% Unhatched	% Parasitized	Parasitoids	Parasitoids species
2021	85	1823	920	903	0	50.47	49.53	0	0	–
2022	47	1141	1086	46	3	95.26	4.03	0.79	9	*Anastatus bifasciatus*

egg masses, comprising 62 eggs, were parasitized. From these three parasitized egg masses, nine parasitoids emerged, all identified as *An. bifasciatus* (Table 3). The overall parasitism rate was 0.79%, with nine parasitized eggs out of 1,141 collected. In both 2021 and 2022, *H. halys* egg laying began in July and continued until early September. In 2022, all parasitized egg masses were found during the first half of August, with no parasitism recorded in other months.

Wild egg masses

In 2020, *H. halys* egg masses were collected from Budapest and Szigetbecse (Hungary), and all the emerged parasitoids were identified as *An. bifasciatus*. In 2021, wild egg masses were collected from more sites in Hungary. In Budapest, 26 egg masses were collected from urban areas, 11 from agricultural areas in Budapest (Soroksár), and 16 from a peach orchard in Érd. A total of 288 and 475 eggs were collected from Budapest (Soroksár) and Budapest, respectively. Notably, 383 eggs were collected in Érd, but no parasitoids emerged from these samples. In Budapest (Soroksár), 13 parasitoids emerged, resulting in a parasitism rate of 4.51%, while in Budapest, 54 parasitoids emerged, corresponding to a parasitism rate of 11.37%. In Budapest (Soroksár), *An. bifasciatus* was recorded from one fully parasitized egg mass, whereas in Budapest, the parasitoid species identified were *An. bifasciatus* and *Ooencyrtus* sp. The co-occurrence of multiple species, such as *Ooencyrtus* sp. and *An. bifasciatus*, within a single egg mass, was also recorded. In 2021, *H. halys* egg masses were also collected from cities in Southeast Europe: Oradea, Sofia, and Novi Sad. A total of 17 egg masses were collected from Oradea, comprising 395 eggs. Out of these, 112 parasitoids emerged, resulting in a 28.35% parasitism rate. The identified species included *An. bifasciatus*, *Tr. mitsukurii*, and *Tr. basalis* (Wollaston). The dominant species was *An. bifasciatus*, with instances of co-occurrence within a single egg mass recorded between *Tr. mitsukurii* and *Tr. basalis*, as well as between *Tr. mitsukurii* and *An. bifasciatus*. In Sofia, only two egg masses were collected, containing a total of 33 eggs. Of these, seven parasitoids emerged, resulting in a 21.21% parasitism rate, and all emerged parasitoids were identified as *An. bifasciatus*. In Novi Sad, four egg masses were collected, containing 107 eggs. Only one egg mass was parasitized, from which 16 parasitoids emerged, resulting in a parasitism rate of 14.95%. Two parasitoid species emerged from this egg mass: *An. bifasciatus* and the exotic species *Tr. japonicus* (Tables 1, 4).

In 2022, egg masses were collected from various locations in Hungary: Budapest, Szeged, and Tarcal. Only one egg mass was collected in Tarcal, with no evidence of parasitism. A total of 45 egg masses were collected from Szeged, corresponding to 1,076 eggs. From the Szeged samples, 74 parasitoids emerged, corresponding to a parasitism rate of 6.88% (Table 1). The parasitoid species recorded were *An. bifasciatus*, *Ooencyrtus* sp., and *Telenomus truncatus* (Nees von Esenbeck). A total

Table 4. Parasitoid species recorded from wild egg masses of *Halyomorpha halys* in 2020, 2021, and 2022.

Location	Year of collection	*Anastatus bifasciatus*	*Trissolcus japonicus*	*Trissolcus mitsukurii*	*Trissolcus colemani*	*Trissolcus basalis*	*Telenomus truncatus*	*Ooencyrtus* sp.
Budapest	2020	9	0	0	0	0	0	0
Szigetbecse	2020	23	0	0	0	0	0	0
Budapest	2021	13	0	0	0	0	0	6
Budapest (Soroksár)	2021	13	0	0	0	0	0	0
Érd	2021	0	0	0	0	0	0	0
Oradea	2021	68	0	23	0	3	0	0
Sofia	2021	5	0	0	0	0	0	0
Novi Sad	2021	2	13	0	0	0	0	0
Szeged	2022	48	0	0	0	0	3	2
Budapest	2022	70	21	0	2	1	0	3
Budapest (Soroksár)	2022	13	0	0	0	0	0	0
Tarcal	2022	0	0	0	0	0	0	0

of 38 and 6 egg masses were collected from Budapest and Budapest (Soroksár), corresponding to 859 and 110 eggs, respectively. The number of parasitoids that emerged from Budapest and Budapest (Soroksár) was 107 and 16, respectively. The parasitism rates recorded were 12.46% for Budapest and 14.55% for Budapest (Soroksár) (Table 1). The parasitoids recorded were *An. bifasciatus* from Budapest (Soroksár) and *An. bifasciatus*, *Ooencyrtus* sp., *Tr. japonicus*, *Tr. basalis*, and *Tr. colemani* (Crawford) from Budapest. Furthermore, *An. bifasciatus* and *Tr. japonicus* were observed in the same egg mass.

In 2021 and 2022, the total number of egg masses collected from agricultural areas was 33, and from urban areas was 160; the recorded parasitoids were 29 and 370, respectively. The parasitoid species observed in agricultural landscapes was *An. bifasciatus*, while in urban areas they were *An. bifasciatus*, *Ooencyrtus* sp., *Tr. japonicus*, *Tr. mitsukurii*, *Tr. basalis*, *Tr. colemani*, and *Te. truncatus*.

During surveys, *H. halys* egg masses were collected from *Ai. altissima*, *Ac. pseudoplatanus*, *F. ornus*, *P. alba*, *Celtis* sp., *Ac. negundo*, *Ac. campestre*, and *Allium porrum* Linnaeus (Amaryllidaceae) (Table 2).

Discussion

A survey examining the egg parasitoids of *H. halys* in Hungary was carried out in 2021 and 2022, during which we identified multiple species of egg parasitoids, including one exotic species. In addition, wild egg masses were obtained from cities in Southeast Europe, specifically Oradea, Sofia, and Novi Sad. This led to the identification of various species of egg parasitoids, including two exotic species. In Hungary, six species of egg parasitoids were discovered, namely *An. bifasciatus*, *Ooencyrtus* sp., *Tr. japonicus*, *Tr. basalis*, *Tr. colemani*, and *Te. truncatus*. *Trissolcus japonicus* is a non-European species that was documented for the first time in Hungary. *Anastatus bifasciatus* was found to be the most predominant and abundant native parasitoid of *H. halys* eggs in Hungary, aligning with earlier European research findings (Costi et al. 2019; Moraglio et al. 2020; Zapponi et al. 2020; Rot et al. 2021; Konjević et al. 2024). In addition, the genus *Anastatus* was among the most retrieved native parasitoids from *H. halys* eggs in the United States (Jones et al. 2014; Dieckhoff et al. 2017).

In 2017 and 2018, an adventive population of *Tr. japonicus* was discovered in Canton Ticino, Switzerland (Stahl et al. 2019b). Later, *Tr. japonicus* was reported from Northern Italy in 2018 (Sabbatini Peverieri et al. 2018), Western Slovenia in 2020 (Rot et al. 2021), Germany in 2021 (Dieckhoff et al. 2021), and in 2024 in Southwestern France (Martel et al. 2024), and Serbia (Konjević et al. 2024). A recent investigation identified *Tr. japonicus* in Hungary for the first time and in Novi Sad, which aligned with the record of *Tr. japonicus* from Serbia by Konjević et al. (2024). The invasion of *H. halys* in North America and Europe has led to the documentation of non-native parasitoids such as *Tr. japonicus* and *Tr. mitsukurii* in invaded areas. In addition, bioclimatic envelope models suggest that *Tr. japonicus* exhibits distinct geographic distribution patterns in Europe, thriving in regions regarded as most suitable for its establishment, including Southwestern France, Northeastern Spain, Northern Italy, Western Slovenia, and Croatia (Avila and Charles 2018; Rot et al. 2021). In the present investigation, *Tr. mitsukurii* was not recorded from Hungary. However, *Tr. mitsukurii* was identified in egg masses collected from Oradea, Romania, which is the first report of this exotic species in the area. According to Tortorici et al. (2023), *H. halys* can thrive and establish in Europe, with the most suitable habitats located in France, Italy, Greece, and some locations in Germany, the Netherlands, and the Balkan Peninsula. Furthermore, the two exotic egg parasitoid species of *H. halys*, *Tr. japonicus* and *Tr. mitsukurii*, were modeled to exhibit distinct geographic distribution patterns in Europe, with *Tr. japonicus* preferring lower latitudes, primarily in the southern part of Europe, and *Tr. mitsukurii* preferring higher latitudes such as Northern and Western France, Belgium, the Netherlands, Denmark, Germany, and Scandinavia. Importantly, it has become apparent that the central part of Europe is favorable to both parasitoid species. Furthermore, Northern Europe, Northern and Eastern Spain, Northern Italy, and the Hungarian Plain may provide ideal conditions for these two *Trissolcus* species but not for *H. halys* (Tortorici et al. 2023). In the current studies, *Tr. mitsukurii* was found in Oradea, located near southeastern Hungary. Consequently, as Hungary is in the preferred zone of these exotic *Trissolcus* species, there is a high probability that *Tr. mitsukurii* is present but undetected in Hungary, or may establish populations in the near future.

Anastatus bifasciatus was the most prevalent *H. halys* egg parasitoid in this study. This observation highlights the ability of native parasitoids to adopt new hosts, indicating their potential to increase the mortality of suitable invasive pest species. Recently, *Tr. mitsukurii*, a non-native parasitoid, was found co-parasitizing BMSB eggs with *An. bifasciatus*, a native parasitoid, thus increasing the overall parasitism rate on *H. halys* in Slovenia (Rot et al. 2021). An attempt to assess the possible coexistence of an exotic Asian egg parasitoid, *Tr. japonicus* (as a classical biological control agent), and a native European egg parasitoid, *An. bifasciatus*, revealed that both species can coexist and possibly act synergistically in increasing rates of *H. halys* egg mortality. The interspecific competition of adults and larvae between these two parasitoid species revealed that they engaged in counterbalance competition, where *Tr. japonicus* was superior as an extrinsic competitor because adults guarded host eggs more aggressively, while *An. bifasciatus* was superior in intrinsic competition because its larvae were more successful in developing from multiparasitized and multi-age *H. halys* eggs (Konopka et al. 2017). Critically, whether the benefits of exotic parasitoids outweigh the risks to non-target species needs to be evaluated in invaded regions. In the present study, the co-occurrence of native and non-native species in a single egg mass was recorded, such as *An. bifasciatus* and *Tr. japonicus*, *Tr. mitsukurii* and *Tr. basalis*, and *Tr. mitsukurii* and *An. bifasciatus*. Therefore, it is feasible that these species could be utilized in future efforts to target the eggs of *H. halys*, provided that the nature of the interaction between the parasitoid species is carefully examined and demonstrated to be beneficial.

Sentinel egg masses on artificial substrates provide a rapid and convenient method for evaluating the presence of natural enemies (Jones et al. 2014), and sentinel egg masses can exhibit higher parasitism and predation rates than eggs laid in sleeve cages (Costi et al. 2019). However, sentinel eggs may underestimate true parasitism rates and misrepresent parasitoid community composition, as they lack host-associated cues present in wild egg masses (Jones et al. 2014). To compensate for the lack of host- and plant-associated cues and to simulate more natural conditions, eggs naturally laid in cages were used in the present study. The average rate of parasitism observed in naturally laid eggs in cages was 0% in 2021, with a marginal increase to 0.79% in 2022. Thus, this method was ineffective for monitoring parasitoid activity in Hungary. The low level of parasitism observed in naturally laid eggs in cages may be attributed to physical barriers, despite the mesh size being sufficiently adequate to allow parasitoids to enter through the netting. Costi et al. (2019) noted a similar outcome when using mesh cages. The collection of wild egg masses was more effective than naturally laid eggs in mesh cages for measuring parasitism rates and parasitoid species diversity, with overall parasitism rates of 5.29% and 8.47% in 2021 and 2022, respectively. Research conducted in Western Slovenia revealed that the average rate of parasitism over two years was 3.0% and 14.4%, with the peak parasitism rate reaching 30.1% (Rot et al. 2021). The level of parasitism observed in this project peaked at 14.55%, which was lower than that reported in Western Slovenia. In the present study, predation was not recorded, and unhatched eggs were not dissected to quantify levels of failed parasitism.

In the present study, urban areas recorded a higher number of *H. halys* egg masses and a greater diversity of parasitoids than agricultural areas. In urban regions, *An. bifasciatus*, *Ooencyrtus* sp., *Tr. japonicus*, *Tr. basalis*, *Tr. colemani*, and *Te. truncatus* were recorded in Hungary; in Oradea, *An. bifasciatus*, *Tr. mitsukurii*, and *Tr. basalis* were found; in Sofia, Bulgaria, only *An. bifasciatus* was observed; and in Novi Sad, Serbia, *An. bifasciatus* and *Tr. japonicus* were recorded. In orchards and agricultural areas surveyed in Hungary, only *An. bifasciatus* was recorded. This highlights the need for further investigation across different orchards and agricultural sites in Hungary to assess the presence of *H. halys* egg masses and parasitoids and to determine if agricultural practices (e.g., insecticide use) affect parasitoid species diversity and abundance.

Anastatus bifasciatus was the most dominant and widespread species in Hungary, followed by *Tr. japonicus*, recorded only from Budapest. In Western Slovenia, the prevalence of *H. halys* egg masses and their parasitoids was significantly greater in suburban and agricultural zones than in urban areas (Rot et al. 2021), where *An. bifasciatus* was the most dominant and widespread species, followed by *Tr. mitsukurii*. Interestingly, Serbia reported a higher incidence of *H. halys* egg masses in hazelnut orchards, whereas the majority of parasitized eggs were collected from urban regions, possibly due to pesticide applications in orchards.

Anastatus bifasciatus was identified as the most dominant and widespread species in Serbia. In addition, *Tr. japonicus* and *Tr. mitsukurii* were also detected; however, the impact of these parasitoids on *H. halys* population densities is not yet assessable, given that parasitoid populations are in early developmental stages (Konjević et al. 2024). In the present investigation, no plant protection products were applied in the agricultural areas (i.e., apple orchards) surveyed at the Hungarian University of Agriculture and Life Sciences Research and Experimental Farm in Budapest (Soroksár) that could have influenced parasitism or species richness. It can be assumed that *Tr. japonicus* may still be in a preliminary stage of its spread across Hungary. However, a more detailed study is required to better estimate its distribution, abundance, and impacts on *H. halys*. In addition, further research is needed to determine the geographic origin of the adventive *Tr. japonicus* and *Tr. mitsukurii* strains using molecular tools. Such investigations could provide greater insight into introduction pathways for adventive biological control agents. The survey of various plant species in Hungary indicated that most wild egg masses (50.56%) and parasitoids (47.83%) were collected from *Ai. altissima*, which aligns with earlier findings (Bergmann et al. 2016; Rice et al. 2014; Bakken et al. 2015). However, in Slovenia, most of the egg masses were collected from – and the highest parasitism rates were recorded from – *Catalpa bignonioides* Walter (Bignoniaceae) and *Ac. platanoides* (Rot et al. 2021). Nielsen and Hamilton (2009) reported that host plant species such as *Ai. altissima*, *Paulownia tomentosa* (Thunberg) Steudel (Paulowniaceae), *Acer* spp., and *Fraxinus* spp. play a crucial role in sustaining *H. halys* populations, especially during the early stages of invasion into a new area. The dispersal capability among various host plants is important for the development and survival of *H. halys*, although this insect can complete its life cycle on *Ai. altissima* and *P. tomentosa* (Funayama 2002, 2004; Rice et al. 2014). These findings are consistent with our observations, since the majority of *H. halys* egg masses were gathered from woody ornamental plants, as listed in Table 2, with the highest recorded figures from *Ai. altissima.*

Conclusion

This research represents the first examination of parasitoids associated with *H. halys* eggs in Hungary, and findings reveal for the first time the presence of the exotic species *Tr. japonicus* in Hungary. This provides valuable insights into the distribution patterns of exotic egg parasitoids of *H. halys* across Europe. Further research is required to better understand the interactions between native and exotic parasitoid species and their use of native and exotic hosts, as well as the mechanisms by which exotic natural enemy species adapt to new environments. Additionally, to improve the design and implementation of biological control programs targeting *H. halys*, further analysis is needed on the diversity, interactions, and abundance of egg parasitoids. Most importantly, future research is needed to assess the following areas with regard to exotic natural enemy species: interactions and competitiveness with native species, survival rate and adaptability, host range and specificity, and suitability for development. Such knowledge is necessary to guide the adoption of classical biological control programs and to determine the best release and establishment strategies. Overall, identifying agronomic practices that are environmentally sustainable and minimize reliance on chemical pesticides is crucial for conserving parasitoid populations while effectively controlling *H. halys*.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Conceptualization: JW, KH, GV, JF. Data curation: JW, KH, FT. Formal analysis: JW, KH. Investigation: JW, GV, FT, KH. Methodology: JW, KH, GV. Supervision: KH, GV, JF. Writing – original draft: FT, JW, KH. Writing – review and editing: KH, JF, PR, KDK, FT.

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Data availability

All of the data that support the findings of this study are available in the main text.

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