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Field performance of the parasitoid wasp, *Trichogrammatoidea armigera* (Hymenoptera: Trichogrammatidae) following releases against the millet head miner, *Heliocheilus albipunctella* (Lepidoptera: Noctuidae) in the Sahel

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Abstract The effectiveness of the egg parasitoid *Trichogrammatoidea armigera* Nagaraja (Hymenoptera: Trichogrammatidae) in controlling *Heliocheilus albipunctella* de Joannis (Lepidoptera: Noctuidae), a major insect pest of pearl millet in the Sahel was assessed during two consecutive years in Niger on-station and on-farm conditions. We found that released *T. armigera* were able to find and parasitize host eggs within pearl millet fields both on-station and in farmers' fields. On-station releases of *T. armigera* led to an average 4.86-fold increase in *T. armigera* parasitism compared to control fields, where no parasitoids were released. Likewise, on-farm releases of *T. armigera* led to up to 5.31-fold more egg parasitism by *T. armigera* in release fields than in control. Our results suggest the effectiveness of *T. armigera* and lays the groundwork for using *T. armigera* in augmentative biological control of *H. albipunctella* in the Sahel.

Keywords Parasitism · Dispersal · Biological control · Augmentative release · Niger

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Introduction

The cropping system in the Sahel typically includes pearl millet, *Pennisetum glaucum* (L.) R. Br. (Poaceae) associated with cowpea, *Vigna unguiculata* (L.) Walp. (Fabaceae), and sometimes sorghum, *Sorghum bicolor* (L.) Moench (Poaceae). Niger is the largest producer of pearl millet with 7.2 million ha (FAO 2019). Over the years, pearl millet grain yields have remained stagnant, usually below 500 kg ha^{-1}. Production is affected by many abiotic and biotic factors, including insect pests. The most important insect pest for pearl millet in the Sahel is the millet head miner (MHM), *Heliocheilus albipunctella* de Joannis (Lepidoptera: Noctuidae). This insect is responsible for chronic yield losses of up to 85% (Krall et al. 1995; Gahukar and Ba 2019). Control measures (cultural control, host-plant resistance, and the application of pesticides) are ineffective, impractical, or not economically feasible (Gahukar and Ba 2019).

Biological control with the larval parasitoid *Habrobracon* (= *Bracon*) *hebetor* Say (Hymenoptera:

Braconidae) has emerged as the most attractive solution for controlling MHM (Gahukar et al. 1986; Bhatnagar 1987). Recently, augmentative releases of *H. hebetor* have been successful against MHM in the Sahel (Payne et al. 2011; Ba et al. 2013, 2014; Baoua et al. 2014, 2018) and a biological control program with *H. hebetor* was designed for Sahelian countries (Guerci et al. 2018). However, the parasitoid *H. hebetor* only targets the third and later instar larvae of MHM when the insect has already started feeding on millet grains (Gahukar and Ba 2019). Early control of MHM may be better achieved with releases of egg parasitoids, especially trichogrammatid species (Hymenoptera: Trichogrammatidae). trichogrammatids have been widely used for biological control of Lepidopteran pests for many decades in different cropping systems (Li 1994; Smith 1996; Jalali et al. 2016; van Lenteren et al. 2018; Parra and Coelho 2019). They have interesting features that make them popular in biological control programs worldwide. They have a short cycle, high reproductive potential, and are usually inexpensive and easy to produce in large numbers on eggs of factitious hosts (Li 1994; Greenberg et al. 1996; Parra 2010; Wang et al. 2014; Jalali et al. 2016). Recently, the parasitoid *Trichogrammatoidea armigera* Nagaraja (Hymenoptera: Trichogrammatidae) was observed to parasitize 12.4% and 17% of MHM eggs in the field in Senegal and Niger, respectively (Karimoune et al. 2018; Sow et al. 2018). Although parasitoids of the genus *Trichogrammatoidea* (Hymenoptera: Trichogrammatidae) are less studied than the related genus *Trichogramma* (Hymenoptera: Trichogrammatidae), they share similar features (Smith 1996) and are both successfully used in augmentative biological control (Newton 1988; Newton and Odendaal 1990; Mohamed et al. 2016; Khatun et al. 2017; Cagnotti et al. 2018). A prerequisite for the use of *Trichogramma* in augmentative biological control requires that large numbers of parasitoids can be efficiently reared (Parra 2010). In the case of MHM, culture of the parasitoid *T. armigera* has been successfully established on eggs of the rice moth, *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae) in Niger (Karimoune et al. 2018). Additionally, laboratory performance of trichogrammatid can be indicative of field performance as indicated by Coelho et al. (2016). In the laboratory, *T. armigera* was found to parasitize nearly 80% of MHM eggs (Karimoune et al. 2018). These results suggest strong potential for the use of *T. armigera* in augmentative releases for MHM control. The present study was a follow-up of early laboratory studies (Karimoune et al. 2018) and is aimed at evaluating the field performance of *T. armigera* after releases against MHM.

Materials and methods

Study environment

The experiments were conducted during two consecutive cropping seasons (May–October in 2017 and 2018) at a research station and in farmers' pearl millet fields in Niger. The on-station experiment was conducted at the research campus for the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Sadore in Niger (latitude 13° 15′ N, longitude 2° 18′ E). The on-farm experiments were performed in selected farmers' fields in villages surrounding the ICRISAT campus in the region of Tillabery that lies between latitudes 13° 13′ 41.03″ and 13° 25′ 09.00″ N, and longitudes 02° 08′ 56.09″ and 02° 18′ 16.05″ E. This agroecosystem has a unimodal rainfall pattern with the rainy season extending from mid-May to mid-October. Total annual rainfall amounts recorded in 2017 and 2018 were 592 mm and 606 mm, respectively. The temperature during the pearl millet growing season was in the range of 20–40 °C, with an average of 28 °C. During this period, the area had continuous pearl millet crops covering almost 80% of the cultivated area, usually in association with cowpea. Farmers grow 2–3 local pearl millet varieties on 3–10 ha. No irrigation, chemical fertilizers, or pesticides were applied to the pearl millet crops.

Insect cultures

The insects mass-reared for this study included the millet head miner, *H. albipunctella*, the rice moth, *C. cephalonica,* and the parasitoid wasp, *T. armigera.* The moths of *H. albipunctella* were collected from five light traps that were set up within the 500 ha area of the ICRISAT Sadore campus. The light trap utilized a 250-W mercury vapor white incandescent bulb wired to a grid. The bulb was positioned above a wire mesh cage (1.38 m width × 1.93 m height), which rested on a metal support set 2.43 m above the ground level. The light trap was operated during the rainy season from June to October in 2017 and 2018. Collected moths were transferred to egg-laying wire mesh cages (30 cm × 30 cm) in the laboratory. A piece of freshly harvested millet panicle was placed in the cage as a surface for MHM moths to lay eggs. The panicle was examined daily, and eggs were collected for use as sentinel eggs for on-station trials.

A colony of *C. cephalonica* was established in the laboratory at ICRISAT Sadore from wild insects collected from farmers' granaries in Niger in 2015. The insects were routinely reared on a mixture of pearl millet grain and flour in plastic buckets at ambient temperature (Ba et al. 2014). Adults typically emerged after one month. The eggs of *C. cephalonica* were used for rearing the parasitoid *T. armigera* and as sentinel eggs for on-station trials. The eggs were irradiated to halt their development, as suggested by Parra (2010), to avoid cannibalization of both parasitized and unparasitized eggs by hatched larvae from unparasitized eggs.

The *T. armigera* parasitoid population was initially started from field-collected eggs of MHM from different regions of Niger as described by Karimoune et al. (2018). Eggs were kept in Petri dishes in the laboratory at the ambient conditions described above until the emergence of adults. Emerging *T. armigera* were collected daily, sexed, and placed in tubes containing freshly laid eggs of the rice moth, *C. cephalonica*. The host eggs were glued on white rectangular cards (4.5 cm × 1.75 cm), and a drop of honey was placed at the corner of the card to provide food for adult parasitoids. The culture was routinely maintained by exposing a first set of 30 eggs (one day old) of *C. cephalonica* to a mated *T. armigera* female. This was followed by subsequent sets of 30 eggs (one day old) every day until the death of the female. The females were given a new male for mating every three days for 24 h. The average life span of *T. armigera* females was approximately 12 days. The development from eggs to adults was completed in seven days. Each female produced approximately 100 individuals in a balanced sex ratio.

Preparation of the *T. armigera* card for on-station and on-farm field releases

All *T. armigera* parasitoids used in the releases were from laboratory colonies reared on a factitious host, *C. cephalonica*. Parasitoid cards (12.5 cm × 9 cm dimension) were prepared seven days prior to field releases. Each card had 14,000 irradiated eggs of *C. cephalonica* parasitized by 250 T. *armigera* mated females for six days. *T. armigera* adults began emerging from cards the day they were placed in the field, and, after three days, all the parasitoids had emerged. Each card produced approximately 8800 parasitoids. The parasitoid cards were placed individually in a thick envelope to protect them from sunlight, direct rainfall, and predation. The envelope was perforated to create small holes that allow emerging *T. armigera* adults to disperse. Given that no recommendation currently exists for the number of *T. armigera* to be released, we released a number of 150,000 parasitoids ha^{-1} (at a sex ratio of 1:1), considering available data on *T. armigera* life table (Karimoune et al. 2018) and the most frequently recommended doses for other *Trichogramma* species in other settings (Bigler 1986; Wang et al. 2014; Tang et al. 2017).

Experimental design for on-station trials

This experiment was performed once in the rainy season of 2017, and twice in the rainy season of 2018. In 2017, the millet was planted in mid-June and panicles began emerging in mid-August. The first trial in 2018 was conducted in an early-planted farm (mid-May) where millet panicles emerged in mid-July, whereas the second trial was conducted in a late-planted farm (mid-July) where millet panicles emerged in mid-September. For each of the three trials an improved popular millet variety named HKP (80 days maturing cycle, sensitive to MHM) was planted at the spacing arrangement of 1 m × 1 m. For each trial, the millet in six fields of 1600 m^2 each and all consecutive fields were separated by 200 m of grassland. The six fields were divided into two groups of three: (1) release fields that were each supplied with *T. armigera* parasitoids and (2) control fields that did not receive parasitoids.

Within each field, millet panicles were randomly selected. A stake flag was used to mark the central point of the field (= 0 m) and in both directions along the NW–SE, SW–NE, E-W and S–N axis at 10 m and 20 m from the central point of the field. At each station, seven panicles were marked. A modified protocol of that described by Chapman et al. (2009)

and Geetha and Balakrishnan (2010) was used for infesting millet heads with sentinel eggs before parasitoid releases. In 2017, we were able to infest only 2.68 panicles per station because of limited MHM eggs. For this reason, in 2018, the marked panicles were infested with either MHM or rice moth eggs to account for the shortage of MHM eggs. The viability of this method was supported by early laboratory findings suggesting equal parasitism of rice moth and MHM eggs by *T. armigera* (Karimoune et al. 2018). We managed to infest 5.15 panicles per station in the 2018 early-planted trial and 6.43 panicles per station in the 2018 late-planted trial. All eggs used in these experiments were irradiated to halt larval development, thus preventing eggs from hatching. Irradiation of MHM and rice moth eggs does not affect their acceptability by *T. armigera* (Karimoune et al. 2018). Infestation was performed at the 30% exertion development stage of the panicle to mimic the preferred oviposition stage of the millet head miner (Karimoune et al. 2018; Owusu et al. 2004). To mimic the preferred oviposition site (Gahukar and Ba 2019), eggs were adhered with non toxic glue to the rachis of the panicle within 3–5 cm of the tip/head. Each selected panicle was infested with 40 eggs of either MHM or rice moth. In 2017, 100% of the treated panicles were infested with MHM eggs, whereas only 7% and 25% of the treated panicles were infested in the 2018 early-planted and late-planted trials, respectively.

Infestation of millet panicles with host eggs occurred on the same day as the placement of parasitoid cards. The parasitoids were released once at the central point of the field using cards with parasitized *C. cephalonica* eggs the day *T. armigera* adults began emerging. The envelopes bearing the parasitoid cards were fastened to a millet stalk at 0.5 m above ground in the central point of the field. All the parasitoids typically emerged in three days (Karimoune et al. 2018). No parasitoids were released in any of the control fields. Eggs of MHM and *C. cephalonica* that were placed on millet panicles in both release and control fields were recollected six days after exposure and taken back to the laboratory for incubation and observation of parasitism, emergence of parasitoids, and dead eggs.

Experimental design for on-farm trials

This experiment was conducted in the rainy season in 2017 and 2018 in selected farmers' fields in the district of Say. For each season, the experiment was performed within three different villages (Deyyebon, Gilliel, and Worseno in 2017; and Mansaré-Boura, Lelehi-Koynounga, and Boumba in 2018). In each village, we selected one early-planted millet farm of at least 5 ha. Early-planted farms are typically more likely to be infested by the millet head miner (Gahukar and Ba 2019). Within that farm, we delineated two plots of 400 m^2 at two ends of the field, such that the two plots were separated by at least 200 m. The two plots were assigned the following treatments: (1) *T. armigera* release fields that were supplied with *T. armigera* cards and (2) control fields that did not receive parasitoids. Each village represents a block with two treatments and three villages represent three replicates. For parasitoid releases, we placed the parasitoid cards after the millet panicle emergence stage and detection of the presence of MHM eggs in the field. We performed one release of the parasitoids at the dose of 150,000 per hectare.

Before the release of *T. armigera*, data on MHM infestation (number of heads-bearing eggs) was recorded on 100 randomly selected millet heads for both *T. armigera* release and control fields. The same observations were performed six days after parasitoid releases, but this time, 100 panicles bearing MHM eggs were taken to the laboratory for assessment of egg parasitism. The eggs were reared in the laboratory at ambient temperature until the emergence of parasitoids. Emerging parasitoids were identified and counted.

Data analysis

The parasitism percentage was calculated by the ratio of the total number of parasitized eggs divided by the total number of collected eggs. For on-station parasitism, MHM and rice moth parasitism was aggregated and computed by treatments as early findings suggest equal parasitism of *T. armigera* for both host species (Karimoune et al. 2018). For each season, data on parasitism and parasitized eggs with viable offspring were subjected to one-way ANOVA to compare release fields with control fields for both on-station and on-farm data. In addition, data of all years were combined together and subjected to two-way ANOVA to compare treatments and years and their interactions. Data were all subjected to arcsine transformation prior to analysis of variance with the SAS software version 9.1 (SAS 2003).

For on-station trials, we also assessed *T. armigera* parasitism at 0, 10, and 20 m distance from release points. When ANOVAs were significant, means were compared by the Student–Newman–Keuls tests at the 5% level. All parameters are presented as mean ± SE.

Results

Parasitism of MHM eggs following on-station releases of *T. armigera*

On average, 74.2 ± 1.81% of sentinel eggs were not recovered from infested millet panicles. However, significantly more egg parasitism by *T. armigera* was recorded in release fields (55–90%) than in control fields (12–16%), irrespective of season and year (2017: $F_{1,4} = 566.14$, $P < 0.001$; 2018-early planting: $F_{1,4} = 40.38$, $P = 0.003$; 2018 late planting: $F_{1,4} = 14.23$, $P = 0.02$; Fig. 1). The overall parasitism for all three years was significantly higher in release fields than control fields (71.51 ± 6.94% *vs.* 14.42 ± 1.34%, respectively; $F_{1,12} = 102.88$, $P < 0.001$). However, a significant difference was not found for the interaction between years and treatments ($F_{2,12} = 2.94$; $P = 0.09$). Once released *T. armigera* dispersed from release point and parasitism was significantly higher at the release point than 10 and 20 m away in both 2018 experiments (Table 1). Likewise, for the combined two experiments, parasitism was significantly higher at the release point than 10 and 20 m away ($F_{2,20} = 14.85$, $P < 0.001$).

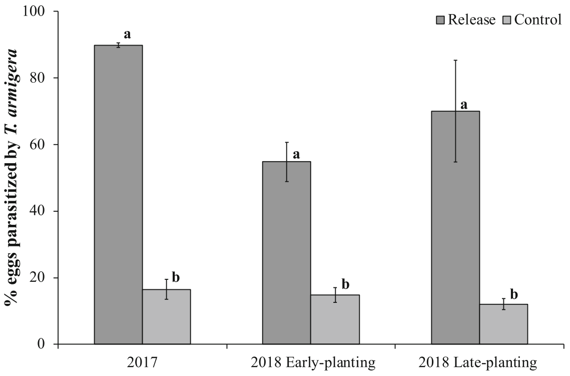

Fig. 1 Parasitized eggs of sentinel host due to *T. armigera* in release and control farm in three successive seasons after on-station releases of *T. armigera*. For each season, bars bearing different letters were significantly different (one-way ANOVA, α = 0.05). Error bars represent SE

Table 1 Parasitism due to *T. armigera* after releases of *T. armigera* on sentinel eggs of millet head miner and rice moth at 0, 10, and 20 m from release point

	Parasitized eggs (% ± SE)	
Distances (m)	2018 Early-planting	2018 Late-planting
0	91.77 ± 4.81 a	97.08 ± 1.81 a
10	46.42 ± 3.57 b	66.67 ± 16.67 b
20	56.88 ± 6.76 b	55.00 ± 5.00 b
	$F_{2,10} = 6.12$; $P = 0.02$	$F_{2,7} = 6.36$; $P = 0.03$

Within a column, means bearing different letters were significantly different (Student–Newman–Keuls test, α = 0.05)

Parasitism of MHM eggs following on-farm releases of *T. armigera*

On average, 25.99 ± 6.98% of millet panicles were naturally infested by MHM in farmers' fields in 2017. The infestation dropped to only 16.05 ± 3.10% in 2018. However, there was no significant difference for head miner infestation between control and release fields in 2017 ($F_{1,4} = 0.001$, $P = 0.98$) and 2018 ($F_{1,4} = 0.44$; $P = 0.54$). The infested panicles had, on average, 11.57 ± 1.64 eggs of the head miner in 2017 and 12.40 ± 2.34 eggs in 2018. Likewise, there was no significant difference between number of eggs recorded in the panicles of control and release fields in 2017 ($F_{1,4} = 1.24$, $P = 0.32$) and 2018 ($F_{1,4} = 0.96$, $P = 0.38$).

The releases of *T. armigera* caused up to 60% egg parasitism by *T. armigera* in release fields compared to up 15% in control fields (2017: $F_{1,4} = 26.39$, $P = 0.007$; 2018: $F_{1,4} = 8.57$, $P = 0.04$; Fig. 2). The overall egg parasitism by *T. armigera* for two years was significantly higher in release fields than control fields (45.40 ± 7.72% *vs.* 10.53 ± 3.86%, respectively; $F_{1,8} = 32.48$, $P < 0.001$). However, a significant difference was not found for the interaction between years and treatments ($F_{2,8} = 2.40$, $P = 0.16$).

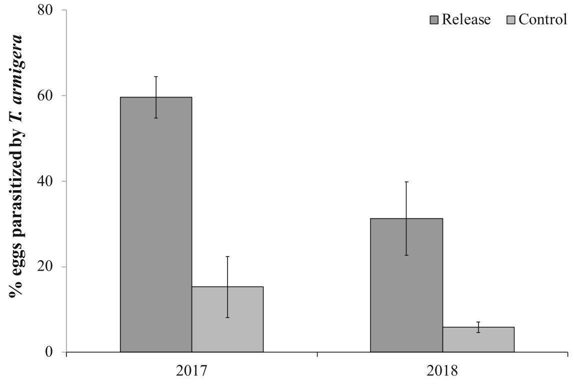

Fig. 2 Parasitized eggs of millet head miner, *H. albipunctella* due to *T. armigera* in release and control farm in 2017 and 2018 after on-farm releases of *T. armigera*. Error bars represent SE

Emergence of *T. armigera* adults from eggs parasitized on-station and on-farm

Typically, the parasitized eggs in release and control fields yielded similar numbers of *T. armigera* progeny in both on-station and on-farm fields regardless of the season, except for the 2018 early-planting on-station experiment (Table 2). For all three years, up to 88% (on-station) and 98% (on-farm) parasitized eggs yielded viable *T. armigera* adults with no significant difference between release and control fields (On-station: $F_{1,12} = 0.15$, $P = 0.70$; On-farm: $F_{1,8} = 0.43$, $P = 0.53$). Likewise, a significant difference was not found for the interaction between years and treatments for on-station ($F_{2,12} = 2.23$, $P = 0.15$) and on-farm parasitoid emergence ($F_{1,8} = 1.36$, $P = 0.27$).

Discussion

In the current study, we found the natural parasitism of MHM eggs due to *T. armigera* in the field to vary between 5 and 16% in 2017 and 2018 on sentinel eggs or naturally laid eggs. This level of parasitism is similar to recent results on the natural parasitism of MHM eggs by *T. armigera* in the same area (Karimoune et al. 2018). This low level of natural parasitism justified the need for augmentative releases (van Driesche and Bellows 1996; Collier and van Steenwyk 2004). Indeed, from the different experiments, releases of *T. armigera* led to significantly higher parasitism of MHM eggs compared to control fields where parasitoids were not released. Similar findings were reported for other trichogrammatid egg parasitoids in open field conditions in corn cropping systems infested with the Asian corn borer, *Ostrinia furnacalis* Guenée (Lepidoptera: Crambidae), and the earworm, *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae) in China (Wang et al. 2014). Likewise, in Latin America, trichogrammatid parasitoid releases significantly increase egg parasitism of *Heliothis virescens* (Fabricius) (Lepidoptera: Noctuidae), *Diatraea* spp. (Lepidoptera: Pyralidae), and *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in crops such as cotton, corn, and sugarcane (Bueno and van Lenteren 2002; Díaz et al. 2012).

Although releases of *T. armigera* increase MHM egg parasitism by 4–5 folds, the overall egg parasitism ranged between 30–90%. This was not unexpected as observed in other settings with other *Trichogramma* species (Bigler 1986; Bourchier and Smith 1998; Parra 2010). However, releases of *T. armigera* will subsequently reduce MHM larvae population in the field.

Table 2 Parasitized host eggs with offspring of *T. armigera* in release and control villages following on-station and on-farm augmentative releases of *T. armigera* in 2017 and 2018

Season	Treatment	Parasitized eggs with offspring (% ± SE)	
		On-station	On-farm
2017	Control	88.18 ± 3.61	76.60 ± 17.08
	Release	64.90 ± 9.13	50.20 ± 10.73
		$F_{1,4} = 5.62$, $P = 0.08$	$F_{1,4} = 1.71$, $P = 0.26$
2018 Early-planting	Control	53.46 ± 5.42	91.11 ± 8.89
	Release	74.10 ± 0.90	97.91 ± 2.79
		$F_{1,4} = 14.13$, $P = 0.02$	$F_{1,4} = 0.53$, $P = 0.50$
2018 Late-planting	Control	53.62 ± 5.91	–
	Release	66.66 ± 24.05	–
		$F_{1,4} = 0.28$, $P = 0.62$	

These larvae will be exposed to natural predation and parasitism (Gahukar and Ba 2019) and ultimately controlled by augmentative releases of the larval parasitoid *H. hebetor* (Ba et al. 2013, 2014; Baoua et al. 2014, 2018). However, this needs further testing as the interaction of different parasitoid species can lead to contrasting results (Briggs and Latto 2001; Finke and Denno 2005; Grieshop et al. 2006; Yamamoto et al. 2007; Bigler et al. 2010).

As indicated by van Lenteren and Bigler (2010), the quality of parasitoids reared in large numbers is critical for use in biological control programs. This suggests that mass rearing should not affect parasitoid performance once released in the field. Furthermore, it can be interesting when released parasitoids produce viable progeny especially when the target pest lays eggs over several weeks. This can evade the need for multiple releases of parasitoids in the same season. Interestingly, our data suggests successful development of *T. armigera* after releases with typical levels of viable progeny that were similar for control and release fields. Given that MHM eggs are laid during a period of six weeks (Gahukar and Ba 2019), the initially released parasitoids will parasitize the first batch of eggs encountered and the emerging progeny could parasitize subsequent eggs being laid by MHM.

Our study showed positive behavior characteristics for *T. armigera* as a biological control agent in pearl millet crops. Results suggest the feasibility of augmentative releases of parasitoids in pearl millet cropping systems as previously reported for the larval parasitoid *H. hebetor* in the same system (Ba et al. 2014; Baoua et al. 2014, 2018; Amadou et al. 2017). We found that released *T. armigera* were able to find and parasitize host eggs within the pearl millet field both for sentinel eggs on-station and naturally infested eggs on farmers' fields. According to Jones et al. (2014), sentinel eggs could dramatically underestimate actual rates of parasitism. In our study, the contrary was observed: the sentinel eggs had significantly more parasitism than wild eggs. Sentinel eggs were also found to be good for estimating parasitism following *Trichogramma* parasitoid releases in many settings (Bourchier and Smith 1998; Wright et al. 2001; Mansfield and Mills 2002; Gardner et al. 2012; Tang et al. 2017). The difference in parasitism by wild and sentinel eggs could be due to the duration of exposure. Sentinel eggs were irradiated and therefore had more exposure to *T. armigera* than wild eggs. Wild eggs could have been there for only a few hours and then collected before being parasitized by *T. armigera*. Nevertheless, the parasitism of sentinel eggs by *T. armigera* could have been overestimated because of the lower number of exposed eggs to released parasitoid ratio. As suggested by on-station data, nearly 75% of the sentinel eggs were not recovered after exposure. This could be due to predation; the millet panicles are visited by several species of mirid bugs and earwigs that prey on MHM eggs (Baoua et al. 1997; Sow et al. 2018). Predation of sentinel eggs has also been reported in other settings (Figueiredo et al. 2002; Chapman 2007; Cornelius et al. 2016; Herlihy et al. 2016). The sentinel eggs could have also been washed away by rain. In fact, 14–40 mm of rainfall was recorded in the 1–4 days following sentinel egg exposure in 2017 and 2018. The data on sentinel eggs is also a good indication of how rain and predators contribute to the reduction of MHM population.

T. armigera parasitism on wild MHM eggs in farmers' fields was higher in 2017 compared to 2018, whereas MHM infestation was lower. This suggests a typical density-dependent behavior as reported previously for *T. armigera* (Karimoune et al. 2018), related species such as *Trichogrammatoidea* sp. nr. *lutea* (Girault) (Kalyebi et al. 2005), and other *Trichogramma* parasitoids (Gross et al. 1984; Wang and Ferro 1998). In our experiment, we released the same number of *T. armigera* regardless of MHM infestation. Since we did not have a recommendation for this parasitoid, we used available data on *T. armigera* life table and most frequently recommended doses for other *Trichogramma* species to start with a dose of 150,000 *T. armigera* per hectare. These findings indicate that the numbers to be released per millet acreage need to be adjusted according to the level of MHM infestation to avoid the release of excess numbers that could lead to superparasitism as reported for *Trichogramma* (Sousa and Spence 2000; Dorn and Beckage 2007; DaSilva et al. 2016), and thus reduce parasitoid efficiency (Knipling 1977; Hoddle et al. 1997; Crowder 2007).

Parasitism at the release point was higher than 10 m and 20 m from the release point. This is consistent with previous studies reporting a decrease in parasitism of *Trichogramma* with increasing distance from the point of release (Greatti and Zandigiacomo 1995; Chapman et al. 2009). In our study, the 10 m and 20 m distances recorded between 46 and 66% parasitism, which is still high. This was higher than the 8 m dispersal observed for *T. pretiosum* released to control Lepidopteran pests in soybean (Bueno et al. 2012) and the 11 m dispersal for *T. brassicae* released for *O. nubilalis* control in corn (Mills et al. 2006). Other studies reported dispersal distances of 45 m and 365 m at four days and 14 days post-release, respectively, for *T. ostriniae* in corn (Wright et al. 2001; Gardner et al. 2012) and potato (Chapman et al. 2009). We cannot speculate about longer dispersal distance for *T. armigera* as our investigation stopped at 20 m from the release point and only lasted six days after post-release. As indicated by several studies, *Trichogramma* dispersal and performance is mainly habitat-specific, which is affected by weather, crop plant architecture, pest cycle, and predation (Thorpe 1985; Andow and Prokrym 1990; Smith 1996; Romeis et al. 1997, 1998; McCravy and Berisford 1998; Cloyd and Sadof 2000; Gingras et al. 2008). For these reasons, the conditions for field release of *T. armigera* needs further investigation. Most important, the timing for *T. armigera* release needs to be identified. MHM moth flight is usually limited to six weeks, and females lay eggs on emerging panicles of millet (Gahukar and Ba 2019). Therefore, there is a narrow window for parasitoid release. Our future investigation will also include the number of parasitoids to be released per area of millet and the number of releases. We will also investigate the effect of *T. armigera* on MHM damage and grain yield and the effect of combined releases of *T. armigera* and the larval parasitoid *H. hebetor* on controlling MHM and the overall effect on millet grain yield. Finally, further investigation will be needed for assessing the economic viability of the technology.

This study showed that augmentative releases of the egg parasitoid *T. armigera* significantly increases the parasitism of MHM eggs in the field. This finding lays the groundwork for use of *T. armigera* for complementing the existing biocontrol program with the larval parasitoid, *H. hebetor* in an integrated approach for controlling the MHM in the Sahel.

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Compliance with ethical standards

Conflict of 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 paper.

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