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ORIGINAL RESEARCH ARTICLE

Integrated pest management strategies for control of the carob moth *Ectomyelois ceratoniae* Zeller (Lepidoptera: Pyralidae) in two oases in the south of Tunisia

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Abstract
Carob moth *Ectomyelois ceratoniae* Zeller (Lepidoptera: Pyralidae) is a cosmopolitan pest that affects many fruit crops under field and storage conditions. In Tunisia, carob moth is regarded as the main phytosanitary problem of pomegranate and date palm. Insecticides are often not a viable option to manage this pest due to the larval stage living inside the plant. This study evaluated the efficacy of an Integrated Pest Management approaches (IPM) including sanitation, mass trapping, inundative releases of *Trichogramma cacoeciae* and date bunch bagging for the control of carob moth on pomegranate and date palm in two oases located in southern Tunisia. Trials were conducted during 2017 and 2018. The findings revealed that an IPM approach to reduce carob moth infestation was quite promising. In both experimental years, fruit damage ranged below 4% on pomegranate and 3% on date palm; furthermore fruit yield was significantly increased on trees where an IPM approach had been applied. *Ectomyelois ceratoniae* egg parasitism reached a maximum of 47.31% (2017) and 52.45% (2018) in pomegranate fruits treated with *T. cacoeciae*. The carob moth population was significantly reduced by 82.68% (2017) and 92.29% (2018) in IPM plots in comparison to control plots. Therefore, the IPM approach proved to be an effective option for achieving sustainable management of carob moth on pomegranate and date palm in oases.

Keywords *Ectomyelois ceratoniae* · Cultural control · Mass trapping · *Trichogramma cacoeciae* · Bunch bagging · Pomegranate · Date palm

Introduction

The Tunisian oases constitute less than 10% of the irrigated areas, but they have significant socio-economic impact in contributing to food security and livelihood diversification for the local population in the desert region (Meftahi et al. 2022). Oases, with their three layers of vegetation, create an ecosystem suitable for the development of biodiversity and for preservation of plant species (Benmoussa et al. 2022). The traditional method adopted in oases is to plant date palm trees (*Phoenix dactylifera* L.) in combination with fruit trees, mainly pomegranates (*Punica granatum* L.).

Date palm is a key element in the resilience of the oasis agro-ecosystem (Djerbi 1993). It is the main agricultural crop on which the sustainable, ecological, social, and economical structures of the oasis are based. The date palm planted area represents about 56.000 ha (with 6 million trees) and it is concentrated in the Djerid and Nefzaoua regions, which are characterized by a saharian climate receiving a quantity of rainfall less than 150 mm/year (Ben Ahmed Zaag 2017). Date production in Tunisia was 310.000 tons in 2020 (Gifruits 2019). The main variety produced in Tunisian oases is the Deglet Noor cultivar (62% of the total number of palm trees), which is highly prized for its organoleptic and nutritional qualities compared to other exported varieties. In fact, this cultivar makes Tunisia the principal supplier to the European market (ONAGRI 2018). The date sector represents 12% of the total value of agricultural exports and

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is second, only to olive oil (ONAGRI 2018). Tunisian dates are exported to more than 80 countries around the world and Tunisia is the first exporter in terms of value (24% of the value of dates world trade) (Ben Ahmed Zaag 2017).

Pomegranate is one of the oldest fruit species in the world, originating in Iran but has became common in the Mediterranean region, the Middle East, and some Asian countries (Evreinoff 1949). In Tunisia, pomegranate is grown throughout the country and is well distributed in oases due to its good adaptation to the limestone soils (which have poor quality), lack of water, high levels of water salinity and arid climate (Mars and Marrakchi 1999). Tunisia is ranked among the top ten producing countries (3% of world supply) (Gifruits 2019). Pomegranate cultivation has increased throughout the last several years, in fact, hundreds of hectares of new plantations are emerging and the national production is increasing rapidly with a growth of 30% between 2018 and 2019 with 75.000 and 97.500 tons, respectively (Gifruits 2019). The Gabsi cultivar is the main variety produced in Tunisian oases and it is well recognized on international markets (Kharchoufi et al. 2018). Pomegranate exports have increased in recent years but they remain low and represents less than 10% of production (Ismail and Hassine 2021).

Pomegranate and date palm crops face many phytosanitary problems, mainly pests. Among these, the carob moth *Ectomyelois ceratoniae* Zeller, 1839 (Lepidoptera: Pyralidae) is one of the most destructive pests, in its larval stage, and is recognized as a polyphagous insect, which is known to feed on 43 hosts belonging to 18 plant families (Perring et al. 2016), of which 21 produce economically important agricultural products (Pintureau and Daumal 1979; Wakil et al. 2015). The larvae cause great economic losses with infestation rates up to 80% in pomegranate (Dhouibi 1982, 1992). Furthermore, the quality and the market value of these fruits are significantly reduced due to the infestation of this pest, particularly the date fruit variety, Deglet Noor, which is the most affected cultivar with a rate of 20% (Khoualdia et al. 1995). In Tunisian oases, the carob moth has 3–4 generations on pomegranate from April until August, depending on climatic conditions. Dates do not become infested by this moth until they begin to ripen in September and the pest can develop 1–2 generations on date palms (Dhouibi et al. 2016).

To obtain suitable quality fruits and a stable yield, control of the carob moth is crucial. Numerous control methods have been explored including mating disruption (Mamay et al. 2016; Dhouibi et al. 2017), mass trapping (Dhouibi et al. 2016; Mamay and Dag 2016; Zougari et al. 2020, 2021), fruit bagging (Sharma et al. 2013), biological control, this strain is commercially available (ControlMed company, Sidi Thabet, Tunisia) (Khoualdia et al. 1996 a, b; Zougari et al. 2020; Zouba et al. 2022), sterile insect technique (Mediouni 2007; Chakroun et al. 2015), mechanical control (Karami et al. 2011; Mamay 2018) and chemical control (Mnif et al. 2013). However, most individual control methods in current use, do not provide much protection against the carob moth (Zougari et al. 2020). Chemical control seems to be inefficient on dates and pomegranates due to the larval development occurring in the plant (Dhouibi et al. 2000; Hached et al. 2018), residue contamination of fruits (Attia el al. 2019; Grissa Lebdi et al. 2020) and a threat to non-target organisms and natural enemies (Basley et al. 2018).

Moreover, the widespread use of insecticides against *E. ceratoniae* lead to the development of resistance to several chemical classes including organophosphates, carbamates and pyrethroids (Alloui-Griza et al. 2022) and the disruption of ecological and environmental balances (Karuppuchamy and Venugopal 2016; Mediouni and Dhouibi 2007). Currently, the Tunisian government has banned the use of broad spectrum insecticides in an effort to protect the oases ecosystem and dates intended for export. Taking into account these concerns, the implementation of an IPM strategy is required to decrease carob moth population densities, reduce fruit damage, and satisfy international regulations and standards necessary for export (Mediouni et al. 2004). Integrated pest management is the integration of a diverse mix of management approaches, plant protection technologies, and appropriate measures that limit the development of pest populations at levels that are economically and ecologically justified and reduce risks to human health (Ehler 2006).

Hence, the objective of this study was to develop and pilot an IPM package in the major date producing oases of southern Tunisia where carob moth is not only an economic pest but a key constraint to agricultural productivity.

Materials and methods

Experimental sites and location

Experiments were conducted during 2017 and 2018 in two oases located in the south-west of Tunisia. The first experimental orchard is in Tameghza region (34°22’52.65"N 7°55’58.79"E) in the governorate of Tozeur. The second is located in Elguettar region (34°19’46.79"N, 8°56’18.41"E) in the governorate of Gafsa. Each orchard had an area of 11.5 ha. The two orchards have similar features in terms of topography, ecology and varieties of date palms and pomegranates. Orchards were selected based on carob moth infestation in previous years and appropriate dimensions for a block trial. In 2016, both orchards had about 83% damaged pomegranates and 21% damaged dates due to *E. ceratoniae*. In each orchard, a randomized complete block (RCB) design with five blocks was used both years. Each block was divided into two plots (1 ha), corresponding to the IPM approach and the control. Plots were separated from each other by an area of 50 m to make sure that treatments did not interfere with the other plot (Sigsgaard et al. 2017). Each plot was planted with 200 date palms of the Deglet Noor variety and 25 pomegranate trees of the Gabsi variety, which are the most susceptible to *E. ceratoniae* (Dhouibi 1992).

Plots treated with the IPM approach (5 treated plots/oasis) received sanitation, mass trapping using delta pheromone traps, inundative releases of *Trichogramma cacoeciae* Marchal parasitoids, and date bunch bagging. Control plots received only sanitation. Experimental orchards did not receive any insecticide treatment before and during the study period. Mass reared *T. cacoeciae* had never been released before 2017.

Integrated pest management measures were initiated with the first capture of *E. ceratoniae* males in pheromone traps and the onset of pest oviposition according to fruit sampling procedures.

Monitoring of environmental parameters

Experimental orchards were equipped with climatic WatchDog® (Spectrum Technologies, USA) data loggers to monitor changes in temperature and relative humidity. Precipitation was recorded from two weather stations located in Tozeur (Tameghza) and Gfasa (Elguettar) (Fig. 1a and b). Both regions have an arid climate with low precipitation; the maximum rainfall registered from February to November 2017 and 2018 was 8 and 14 mm in Tozeur and Gafsa, respectively. For the same period, the mean temperature as well as relative humidity in Tameghza oasis varied from 9.2 to 39.25 C° and from 18 to 67%, respectively (Fig. 1a). In Elguettar oasis, the mean temperature ranged from 8 to 36.5 °C and the mean relative humidity ranged from 22 to 87% (Fig. 1b).

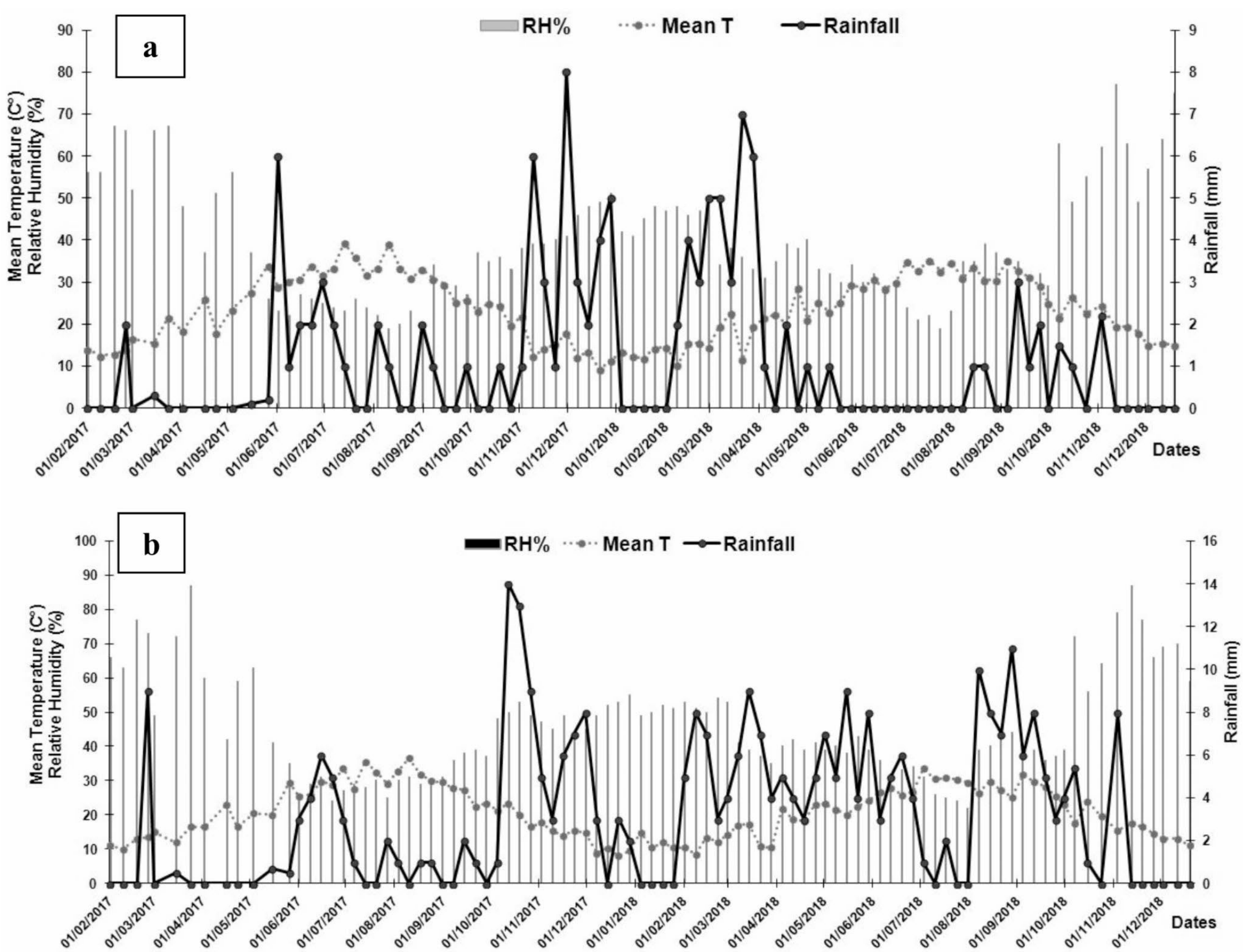


Fig. 1 Climatic conditions in Tameghza (**a**) and Elguettar (**b**) from February 2017 to December 2018

Ectomyelois ceratoniae integrated pest management strategies

Prevention and sanitation

In early February, prophylactic measures were applied in all experimental plots by collecting and destroying the infected dates and pomegranates that have fallen to the ground, as well as those remaining on the trees or at the palm stipe, heart, and foliage to eliminate sources of reinfestation. Damaged fruits were collected in plastic bags, put into garbage containers and buried outside the research area.

Mass trapping

The flight activity of *E. ceratoniae* males in control and IPM plots was monitored by placing two delta traps (Koppert Biological System) per plot (1 ha) in early February 2017 and 2018. Traps were baited with the sex pheromone of *E. ceratoniae* female ((Z,E)-7,9,11,-dodecatrien-1-ol formate).

Mass trapping was conducted on pomegranate and date palm trees on 07 March 2017 and 09 March 2018 in all IPM plots using 12 delta traps/ha as described by Zougari et al. (2021). Traps were stapled to the trunk of the trees at a height of 1.5 m above ground level (oriented in the same cardinal direction) and checked once a week during the study period. Pheromone lures and sticky cardboards were changed every 4 weeks.

Field releases of Trichogramma cacoeciae

The indigenous strain of *T. cacoeciae* used in this experiment was originally isolated from eggs of *E. ceratoniae* in Tunisian date palm groves and identified by Khoualdia (1995). Parasitoids were received as pupae in *Ephestia kuehniella* eggs on small cardboard cards (1 × 5 cm). A releasing card held 1000 parasitized eggs of *E. kuehniella*.

Three inundative releases of *T. cacoeciae* (at the density of 25.000 Trichogramma/ha) took place from 11 June to 16 August 2017 and from 07 June to 14 August 2018 at four week intervals to cover the occurrence of the three generations of *E. ceratoniae* on pomegranate. One releasing card was hung in the middle of each of the 25 pomegranate trees in each IPM plot as described by Zougari et al. (2020). At the end of the treatment, a total of 150.000 *T. cacoeciae* were released in each IPM plot.

Cardboard cards are protected by waxed card capsules (approx. 5 cm^3) with 0.75 mm mesh screen, thus allowing emerging *T. cacoeciae* to pass but excluding predators such as ants from entering and possibly damaging the *Trichogramma* pupae (Zouba et al. 2013). Furthermore, the experimental trees were protected against ants coming up from the soil by rat's glue applied on the base of the tree, 15 cm above the ground before each release. The releasing capsules were placed on the interior terminal branches of trees, in the southern direction, at a height of 1.5 m, to protect the *Trichogramma* pupae from unfavorable weather conditions at the outer area of the canopy.

Results of inundative releases of *T. cacoeciae* may be affected by naturally occurring parasitoids of the genus *Trichogramma*. Thus, 30 bait cards/ha were placed in control plots during the spring (Mars/April/ May) and summer (June/ July/ August) of 2017 and 2018.

Since baitings for naturally occurring *T. cacoeciae* were unsuccessful (natural parasitism < 4%), it can be assumed that the natural population was low and would not significantly affect the experiment.

Emergence and parasitism rate of *Trichogramma cacoeciae*

To assess the emergence rate of *T. cacoeciae* females, ten cardboard cards were removed from each experimental plot two weeks after each release and examined under a binocular microscope (Leica® model MS5/ X10). Numbers of hatched and unhatched eggs were counted to compare the emergence rate between open field conditions and laboratory conditions. The emergence rate was calculated according to the following formula:

Emergence rate = (Number of eggs with emerged parasitoids/ Total number of eggs) x 100.

In order to estimate the parasitism rate, 10 pomegranate trees were randomly selected and marked in each experimental plot. From each tree, two fruits from each cardinal direction (east, west, north and south) were sampled weekly and checked for egg parasitism (i.e., a total of 80 randomly chosen pomegranate fruits for each monitoring date). In the laboratory, fruits were examined and eggs of *E. ceratoniae* were kept in a climatic chamber (25 ± 1 °C, 70 ± 5% RH and a 16:8 (L:D)). Eggs were checked daily under a binocular microscope and those hatching were recorded. Parasitized eggs were easily identified by their black color and their number was recorded. The parasitism rate was determined as follows:

Parasitism rate = (Total number of parasitized eggs of *E. ceratoniae*/ total number of eggs) x 100.

Bunch bagging treatment

This experiment was carried out on female date palms of the Deglet Noor variety. Palms in experimental orchards are all at similar age (45 years old), uniform in growth and size (between 8 and 9 m), and subjected to the same management and cultural practices. Palms were manually pollinated in April of each year and a total of 12 bunches were left on each tree. Net bag size was 150 cm L (Length) x 90 cm W (Width). The upper part of the net (90 cm long) is made from white synthetic fiber to protect the bunches from rain, while the lower part (60 cm long) is made from perforated transparent polyethylene (perforations diameter: 100 µ) to improve aeration and prevent egg laying by *E. ceratoniae* on date fruits (Fig. 2). The bunch covering treatment was conducted at the beginning of fruit color break stage (15 August) and bunches remained covered until harvest date in the second week of October. This treatment was applied on each date palm in the IPM plots. The net bags were installed by lifting the open end of the net around the date bunch, gathering the excess material tight around the bunch stalk, and tying the net closed around the stalk with a plastic wire.

Assessment of the infestation rate

Pomegranate fruit damage rate was assessed every week from the beginning of IPM treatments until the ripening period (September 2017–2018), corresponding to 24 assessments during the trial period. In each plot, 5 pomegranate trees were randomly selected and marked. The total number of pomegranate fruits and the number of infested fruits present on (attached) and under (dropped) the marked trees were counted weekly.

Date fruit sampling was performed just before bunch covering treatment and at harvest when fruits reached full maturity (17th October 2017 and 19th October 2018). In each experimental plot, the infestation rate of fruits was determined on 15 date palm trees. For each palm tree, date fruit samples were randomly and systematically taken from 12 bunches (3 bunches in each cardinal orientation) at the rate of 50 fruits per date bunch (i.e., a total of 9 randomly chosen date fruits at harvest).

Fruit samples were examined in the laboratory and every observed stage of *E. ceratoniae* referred to an infested fruit. The infestation rate was calculated according to the following formula:

Infestation rate = (NA/NB) *100. Where: NA: the number of infested fruits, NB: the total number of fruits.

The reduction rate was calculated according to Abbott (1925) as follows:

Reduction rate = ((A-B/A) *100). Where: A: the mean infestation of date fruits/ week in the control treatment, B: the mean infestation of date fruits/ week in treated plot.

Statistical analysis

Data on the effectiveness of an IPM srategy were analyzed using the software IBM SPSS (Statistics 20). General linear model procedures were used to perform the analysis of variance. Wherever significant difference occurred, Tukey's multiple comparison test was applied for mean separation.

The percentages of infestation and efficacies of IPM were evaluated as either:

1. The percentage of infestation= $\mathbf{(N_A/\ N_B)*100}$.

$\mathbf{N_A}$ is the number of infested pomegranate fruits per tree and $\mathbf{N_B}$ is the total number of pomegranate fruits per tree.

2. Abbott formula (1925): the reduction percentage= **[(A-B/A)*100].**

A is the mean infestation of pomegranate fruits per week in the control treatment and **B** is the mean infestation of pomegranate fruits per week in the treated plot.

Pearson correlation analysis was used to assess the relationship between *T. cacoeciae* releases and the parasitism rate of *E. ceratoniae* eggs.

Results

Assessment of the efficacy of an Integrated pest management approach

Assessment of *Ectomyelois ceratoniae* male population

Prior to IPM treatments applications in 2017 and 2018, the number of males caught in Delta traps did not differ significantly among plots neither in Tameghza ($p=0.985$) or in Elguettar ($p=0.663$).

In Tameghza oasis, the moth population remained low in IPM plots during the entire season (March-October). There was a significant difference between IPM and control plots for the number of captured males by Delta traps during 2017 (F (3,43) = 8,65, $p<0{,}05$) and 2018 (F (2,45) = 9,43, $p<0{,}05$). Male density was reduced by 87.05% in 2017 and by 96% in 2018. Compared to 2017, the total number of trapped males in IPM plots was significantly decreased in 2018 ($p=0.02$) (Fig. 3a, b).

Flight activity of *E. ceratoniae* in Elguettar oasis is shown in Fig. 3 (c, d). During the two experiment years, the moth population remained low in the IPM plots (<4 males/trap per week in 2017 and <2 males/trap per week in 2018). Statystical analysis showed a significant difference between IPM and control plots for the number of captured males during 2017 ($F_{3,\ 34}$=6.75; $p=0{,}003$) and 2018 ($F_{2,\ 43}$ = 8.77; $p=0{,}001$). Male density was reduced by 78.06% in 2017 and by 82.41% in 2018.

Fig. 2 Date bunches protected from *Ectomyelois ceratoniae* by net bags

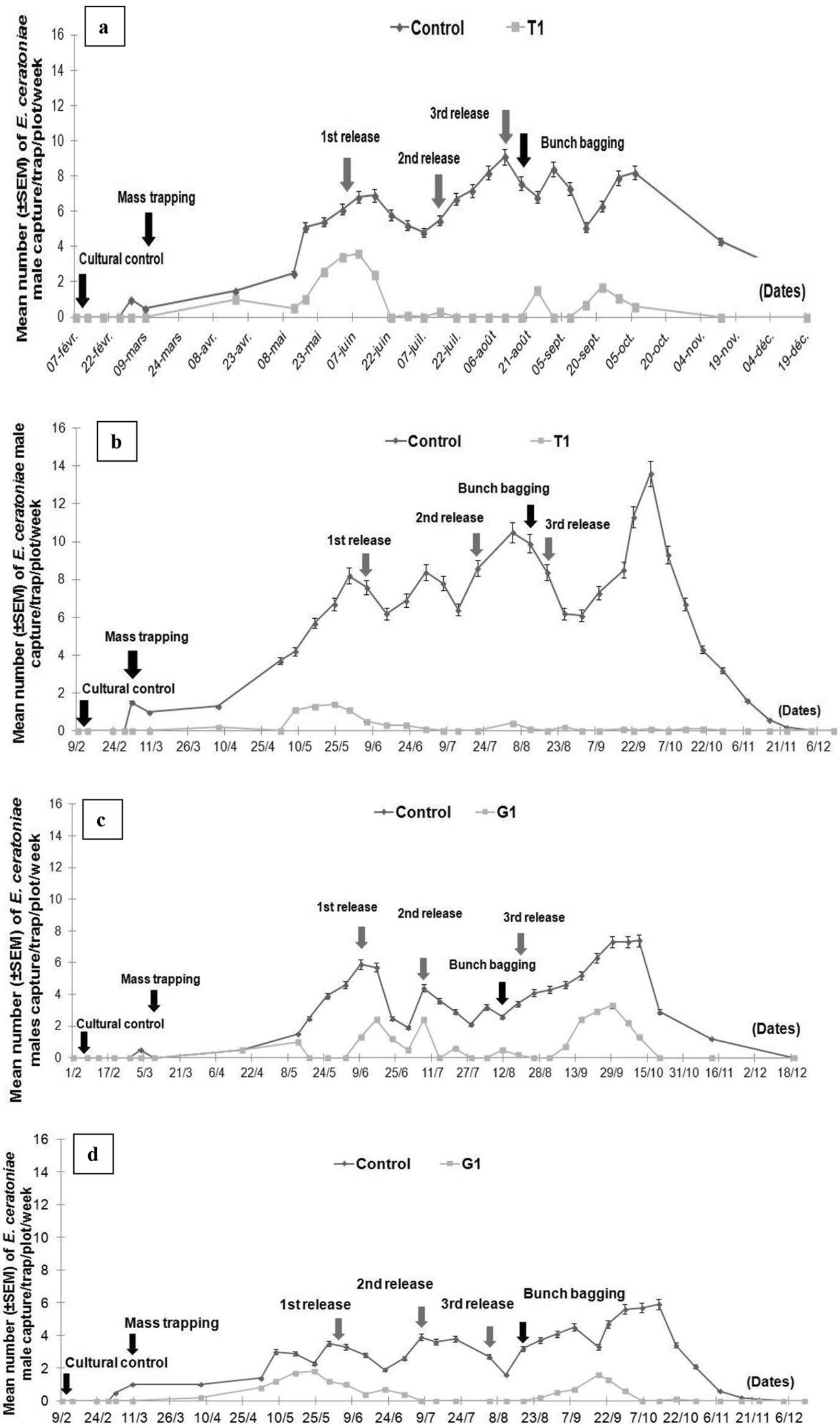


Fig. 3 Weekly captures (± SE) of *Ectomyelois ceratoniae* males by Delta traps in Tozeur (T1: Tameghza/ (**a**, **b**)) and Gafsa (G1: Elguettar/ (**c**, **d**)) during 2017 and 2018 [*E. ceratoniae* management measures]

Assessment of Trichogramma cacoeciae releases

Emergence rates In Tameghza oasis, the average numbers of emerged adults in IPM plots during 2017 and 2018 were 837 ± 5.12 and 954 ± 1.04 *T. cacoeciae*/1000 parasitized eggs corresponding to emergence rates of 83.7% and 95.4%, respectively. The emergence rate did not vary significantly in the field compared to control under laboratory conditions with (93.6%) ($P < 0.05$). As shown in Table 1, emergence rates recorded after the first, second and third releases were similar and relatively high, ranging from 79.3 to 96.6%.

In Elguerttar oasis, statistical analysis of the obtained results showed no significant difference in emergence percentage of parasitoids between the field and control during 2017 ($p = 0.987$) and 2018 ($p = 0.663$). During the two experiment years, emergence rates registered after the three releases of *T. cacoeciae* were relatively high, varying from 76,3%. to 94,5% during 2017 and 2018, respectively.

Parasitism rates Parasitism started at low levels in June, but increased throughout the season. In both experimental years, statistical analyses showed a positive and significant correlation between number of *T. cacoecaie* releases and parasitism rate of *E. ceratoniae* eggs inTozeur ($r = 0.908$; $p = 0.001$) and Gafsa ($r = 0.917$; $p = 0.000$) (Fig. 4). Maximum parasitism rates were recorded in Tameghza and Elguettar during the last release (3rd) in pomegranate fruits with 32.45 ± 9.87% and 29.56 ± 6.42% and 52.45 ± 8.93% and 49.66 ± 8.5% during 2017 and 2018, respectively. When total parasitism over the total season was considered, statistical analysis showed that parasitism rates were similar in Tameghza and Elguettar oases during 2017 ($p = 0.932$) and 2018 ($p = 0.887$).

Field infestation by *Ectomyelois ceratoniae* on pomegranate trees

In both 2017 and 2018, fruit damage rates on the first assessment date did not differ significantly among IPM and control plots in the Tameghza and Elguettar sites.

In Tameghza, a significant reduction in carob moth infestation on pomegranate fruits was observed between the control and IPM treated plots during 2017 ($F_{(2, 22)} = 16.157$; $p = 0.003$) and 2018 ($F_{(2, 22)} = 13.56$, $p < 0.05$) (Fig. 5a). In both years, the highest percentage of damaged fruits was recorded during harvest in control plots with 21.63 ± 6.56% and 20.01 ± 4.14% compared to 3.46 ± 0.97% and 1.56 ± 0.85% in IPM plots, respectively in 2017 and 2018. Therefore we registered a reduction rate of 84% and 92.25% in 2017 and 2018, respectively.

In Elguettar, the effect of an IPM approach on pomegranate fruit damage was significant, with a higher percent of damaged fruit in the control than in treated plots (2017: $F_{(2, 22) =}$ 14.56; $p = 0.002$ / 2018 $F_{(2, 22)} = 15.34$; $p = 0.001$) (Fig. 5b). At harvest time, 19 and 21 September 2017 and 2018, respectively, the infestation rates in control plots were 8 and 9 times higher than in IPM plots, respectively.

Field infestation by *Ectomyelois ceratoniae* on date palm trees

In both oases, no fruit damage by larval feeding was detected in IPM and control plots before bunch covering treatment during 2017 and 2018. In Tameghza oasis, the infestation rate of date fruits at harvest was significantly higher in the control plots with 22.56 ± 9.24% (2017) ($p < 0.005$) and 23.86 ± 10.87% (2018) ($p = 0.003$) compared to 2.03 ± 0,11 and 1.65 ± 0.05% in IPM treated plots, respectively (Fig. 6a). Therefore, we registered a reduction rate of 91 and 93.08% in 2017 and 2018, respectively. In Elguettar oasis, IPM plots had significantly lower fruit damage rates than control plots (Fig. 6b) and the infestation rates of fruit were reduced by 90.43% in 2017 and by 94.15% in 2018.

Discussion

Ectomyelois ceratoniae male population

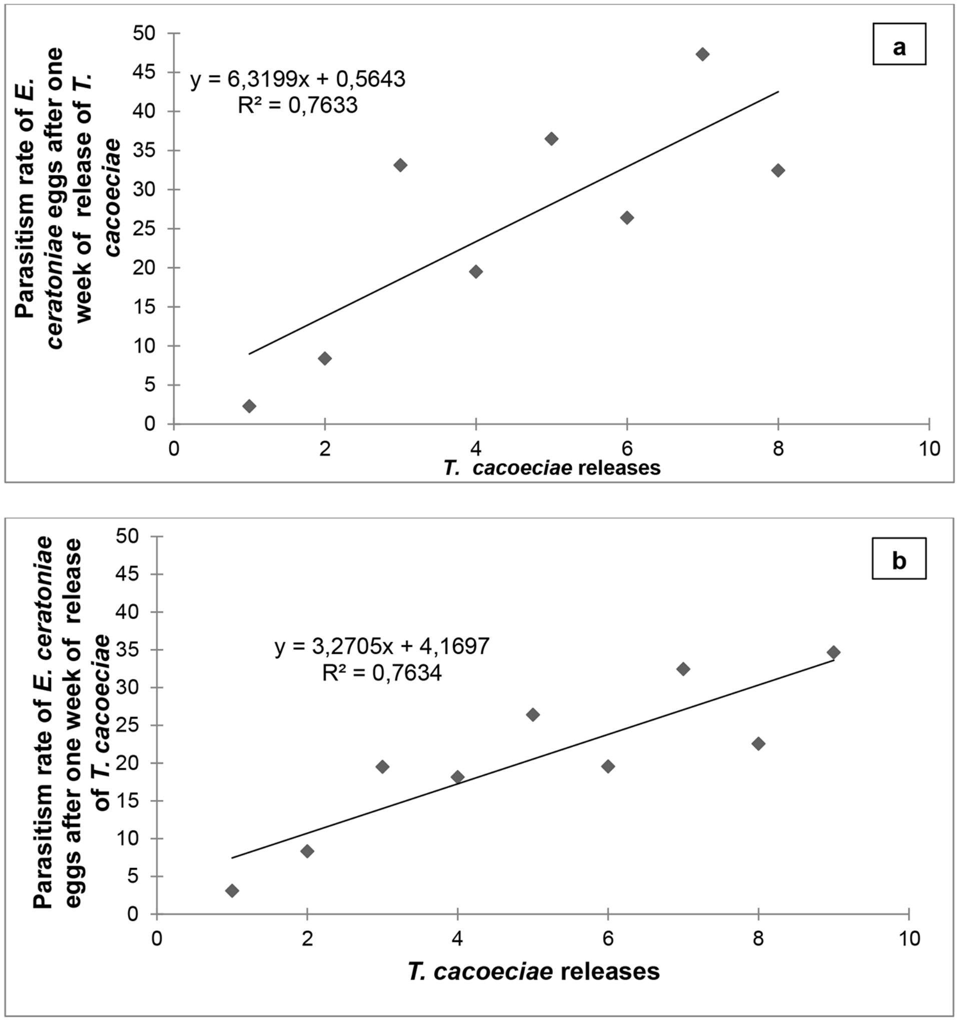
In the present study, pheromone traps are used to monitor the seasonal flight period and the abundance of carob moth in pomegranates and date palms in Tameghza and Elguettar. Results revealed the absence of the pest during February 2017 and 2018, which can be related to weather conditions in these areas and especially to temperatures, which are below 15 °C. Nay et al. (2008) showed that high levels of survivorship of all stages of *E. ceartoniae* reared on date fruits were observed over the range 15–35 °C with

Table 1 Emergence rates (%) of *Trichogramma cacoeciae* in experimental sites and laboratory conditions

	2017			2018		
	Release1	Release2	Release3	Release1	Release2	Release3
Tameghza	79.5 ± 9.63a	86.9 ± 8.54a	85.3 ± 11.25a	93.7 ± 6.71a	96 ± 8.46a	96.6 ± 10.23a
Elguettar	76.3 ± 11.14a	89.7 ± 11.47a	93.6 ± 8.69a	88.4 ± 5.74a	94.5 ± 2,42a	92.4 ± 8.75a
Under Laboratory	89.1 ± 7.34a	91.2 ± 7.16a	95.2 ± 10.22a	94.6 ± 9.76a	96.7 ± 7.63a	95.1 ± 5.49a

The different letters in the rows indicate significant differences between the emergence rate in laboratory compared with that in oases ($p < 0.05$)

Fig. 4 Relationship between *Trichogramma cacoeciae* releases on pomegranate fruits and parasitism rate of *Ectomyelois ceratoniae* eggs during 2017 and 2018 in Tozeur (**a**) and Gafsa (**b**) oases



a maximum at 32 °C, which was consistent with the previous studies of Mediouni and Dhouibi (2007). Our results showed the presence of four generations of *E. ceratoniae*/year on pomegranate and date palms from March 2017 to October 2018. The major peaks of male catches registered in August and October correspond to the 3rd and 4th generations and coincide with pomegranate and date ripening periods, respectively. Flight periods of the carob moth are not identical between studies. According to Abid et al. (2021) and Dhouibi et al. (2016), the number of generations varies depending on changes in climatic conditions, available host plants, year, and sites. In Tunisia, Ben Ayed (2006) and Mejri (2008) reported that the carob moth may accomplish four generations on pomegranate orchards in the center and in the north of the country. However, Jammazi (1994) and Lebdi Grissa et al. (2020) noted the presence of only two generations on pomegranate and date palm trees in the southwest of Tunisia. Hached et al. (2021) reported the presence of 5 generations on orange Thomson variety in citrus orchards in the north of Tunisia. According to Mamay et al. (2014) and Naseiran et al. (2013), the carob moth may accomplish four generations on pomegranate trees in Turkey and in Iran. In the United States of America and Iraq, Nay and Perring (2008) and Al-Izzi et al. (1985) noted the presence of 5 generations on date palm trees.

Mass trapping technique

Mass trapping was used successfully against lepidopterans such as the codling moth *Cydia pomonella* Linnaeus (El Sayed et al. 2006), the tomato leafminer *T. absoluta* (Aksoy and Kovanci 2016), the lesser date moth *Batrachedra amydraula* Meyrick (Levi-Zada et al. 2017), the European grapevine moth *Lobesia botrana* Denis & Schiffermüller (Rayegan et al. 2016) and the gypsy moth *Lymantria dispar* Linnaeus (Charelton and Cardé 1990). Recently, the mass trapping technique has received much attention with regards to carob moth management and different pheromone traps had been evaluated in many countries including Turkey (Demirel 2016), Iran (Mehrjardy et al. 2016), Algeria

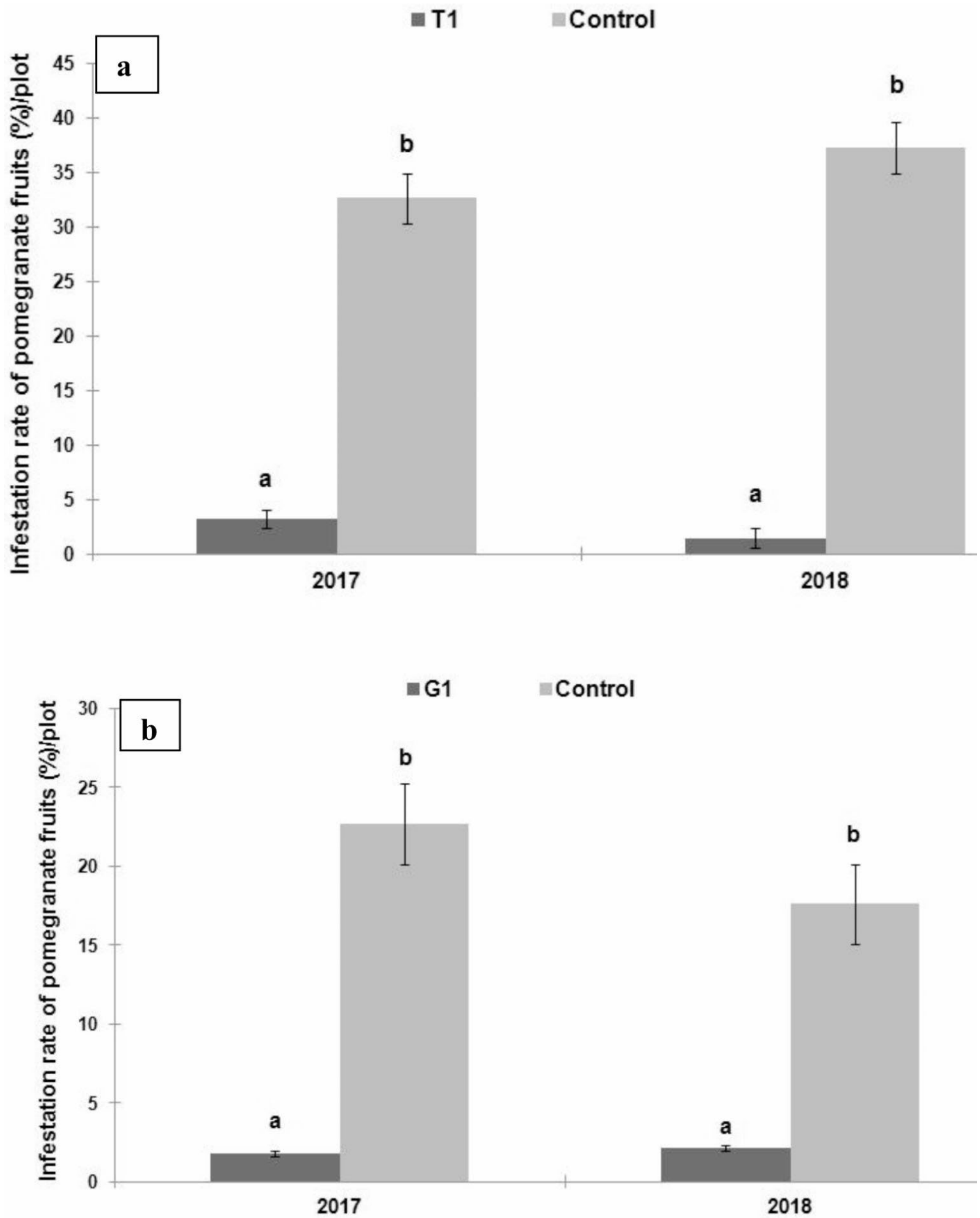


Fig. 5 Mean infestation rate (%) of pomegranate fruit caused by *Ectomyelois ceratoniae* in Tozeur (**a**) and Gafsa (**b**) oases during 2017 and 2018 (T1: Tameghza; G1: Elguettar) Different letters above the bars indicate significant differences ($p \leq 0.05$; Tukey's test)

((Eiras 2000) and Tunisia (Dhouibi et al. 2016; Ben Chaaben and Mahjoubi 2019; Zougari et al. 2021). Our results showed a considerable capacity of capturing *E. ceratoniae* males through Delta pheromone traps. The highest numbers of captured males were recorded in control plots with 146.8 and 99.8 males/trap in Tameghza orchard and 180.2 and 81.3 males/trap in Elguettar orchard, during 2017 and 2018 respectively. Zougari et al. (2020) showed that Delta traps captured significantly more males of *E. ceratoniae* compared to water traps; 483 individuals were captured by Delta traps with a density of 14 traps/ha on pomegranate trees against 152 individuals captured by water traps with the same density. In Iran, Mehrjardy et al. (2016) showed that captured *E. ceratoniae* males by Delta traps were high; 841 and 722 individuals in pomegranate and fig orchards, respectively. However, several studies showed that carob moth infestations remained high when mass trapping technique was used alone. Zougari et al. (2021) revealed that mass trapping applied on date palm trees was not sufficient to limit economic losses in Tunisia. A mass trapping study by Delta traps (14 traps/ha) on pomegranate in Tunisian oases showed that carob moth infestation rate was 17.6% (Zougari et al. 2020). Likewise, Mamay and Dag (2016) reported an infestation rate of 16% for mass trapping (20 traps/ha) in pomegranate orchards in Turkey.

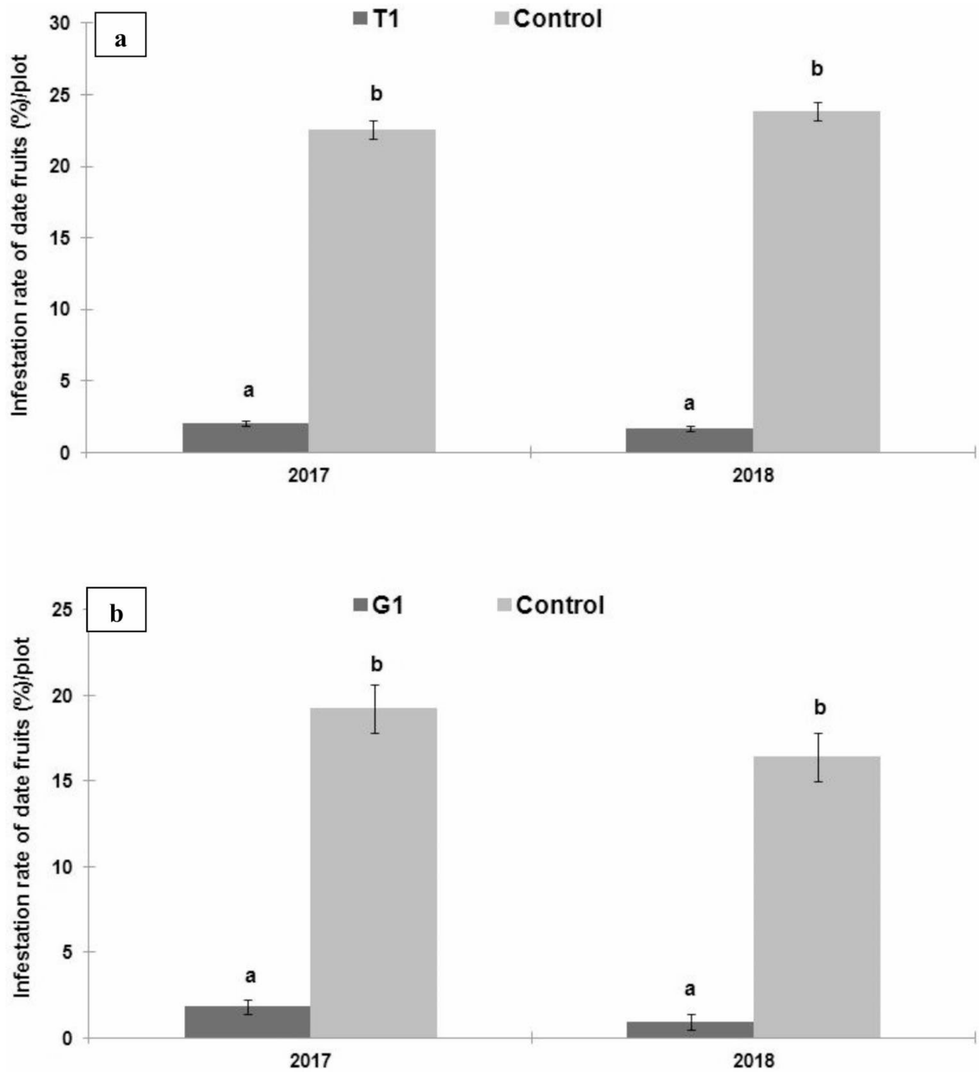


Fig. 6 Comparison of the mean rate of infestation of date fruit caused by *Ectomyelois ceratoniae* during harvest in Tozeur (**a**) and Gafsa (**b**) oases between treated plots (T1: Tameghza; G1: Elguettar) and control plots during 2017 and 2018
Different letters above the bars indicate significant differences ($p \leq 0.05$; Tukey's test)

Trichogramma cacoeciae release

Among natural enemies of the carob moth, the facultative gregarious parasitoids of the genus *Trichogramma* are small wasps that oviposit predominantly in the eggs of a large number of crop pests (Chailleux et al. 2013). Currently, about twelve *Trichogramma* species are widely used in biological control programs against Lepidoptera pests (Barnay et al. 2001; Hegazi et al. 2012; Dionne et al. 2018), due to their economically reasonable mass rearing procedure and their potential to eliminate the pests even before they began to cause feeding damage (Hafez et al. 1999). Different native species of *Trichogramma* have been evaluated for controlling the carob moth (Moezipour 2006). In particular, *T. cacoeciae* is a thelytokous parasitoid, which was reported to be present in many countries in Europe and North Africa (Herz et al. 2007). In Tunisia, *T. cacoeciae* was reported on several crops such as olive (Herz et al. 2007), pomegranate (Ksentini et al. 2010), and date palm (Zouba et al. 2013).

Trichogrammatids are generally polyphagous parasitoids (Smith 1996). However, many studies showed their preference for some host species (Hassan 1989; Attic et al. 2001; Goulart et al. 2011). As suggested by several authors, the screening of biocontrol agents should include indigenous species due to their better adaptation to the proposed climate, habitat, and host conditions (Messing and Wright 2006; Ksentini and Herz 2019). These requirements were taken into consideration in our work. In fact, the *T. cacoeciae* strain used in this study was collected from oases of southern Tunisia where extreme climatic conditions are prevalent (Khoualdia et al. 1995) and it showed a preference for parasitism over *E. ceratoniae* eggs compared to other hosts such as *T. absoluta* eggs (Zouba 2016; Cherif et al. 2019).

The emergence rates of *T. cacoeciae* in Tameghza and Elguettar IPM plots were relatively high and similar to laboratory studies ranging between 76.3 ± 11.14 and $95.2 \pm 10.22\%$ and 88.4 ± 5.74 and $96.7 \pm 7.63\%$ in 2017 and

2018, respectively. The high diversity and density of trees and herbaceous plants in addition to irrigation via the flood system provided a favorable microclimate for *T. cacoeciae* in experimental orchards. In fact, during the entire seasons of 2017 and 2018 we registred adequate temperature (16–31 °C) and relative humidity (R.H ≥ 50%) conditions. Similarly, Zouba et al. (2021) revealed that *T. cacoeciae* emerged successfully from *E. kuehniella* eggs (emergence rate > 90%) at 15, 20, 25 and 30 °C, under controlled conditions. Also, in a study conducted in the Nefleyette oasis (governorate of Tozeur), Zougari et al. (2020) showed that the emergence rate of *T. cacoeciae* released on pomegranate and date palm trees against the carob moth was 94.8%. However, Zouba et al. (2022) showed that the emergence rate of *T. cacoeciae* in Douz oasis (characterized by the monoculture of Deglet noor variety) was relatively low, varying from 34.2 to 48.6%. According to the same authors, several factors may disrupt wasp emergence in field, especially climatic conditions and predation. Furthermore, Alloui-Griza et al. (2022) mentioned that the emergence rate of *T. cacoeciae* was lower in citrus orchards (61.3 – 79.26%) as compared to the laboratory (90.08 – 94.67%) and they explained this difference by several factors including the rearing temperature of parasitoids, the quality of the host eggs, and the storage conditions of parasitoids. In this study, we noticed that predation did not reduce the number of parasitoids available for emergence in the field below those originally planned. Thanks to releasing capsules, cardboard cards were not attacked by predators. Similarly, Pizzol et al. (2010) and Usman et al. (2015) showed that predation was not observed in cotton and apple orchards treated with encapsulated *T. exiguum* and in corn treated with encapsulated *T. brassicae*, respectively. However, predation has been reported in other studies in which the encapsulated material was not used, with losses up to 30% in date palm, 50% in corn, and 91–98% in cotton (Reay-Jones et al. 2006; Zouba et al. 2022).

Our results showed that releases of *T. cacoeciae* resulted in moderate parasitism on carob moth eggs. The highest parasitism rates were recorded after the 3rd release with 47.31% and 31.33% and 52.45% and 42.78% in Tameghza and Elguettar orchards during 2017 and 2018, respectively. Compared to previous studies in Tunisian oases using *T. cacoeciae*, the parasitism rate on *E. ceratoniae* eggs reached 41.45% (Zougari et al. 2020) and 78.7% (Khouladia et al. 2008). In Algeria oases, the parasitism rate of *T. embryophagum* and *T. cordubensis* on *E. ceratoniae* eggs was 47 and 64%, respectively (Idder et al. 2009). In Iranian pomegranate orchards, Mirkarimi (2000) showed that the parasitism rate on *E. ceratoniae* eggs increased from 17.5% under natural conditions to 53.1% after *T. embryophagum* releases. Parasitism rates reported for previously tested *Trichogramma* species may be influenced by the habitat (Kabiri et al. 1990), the crop (Sigsgaard et al. 2017), the host egg (Brotodjojo and Walter 2006), the number of released parasitoids (Chailleux et al. 2013; Sarhan et al. 2015), the spacing among release points (Sarhan et al. 2015), and the interval between *Trichogramma* releases (Zhang et al. 2010).

Bunch bagging paractice

Bunch bagging is practiced on many date palm cultivars and its use is increasing in several countries to improve the commercial value and securing the export market of date fruits (Baer and Kaufman 2012). This technique showed a beneficial effect on fruit quality and yield, in fact, bagging offers several advantages to protect date fruits from high humidity, rain and damage caused by birds, insect pests and diseases (Khoualdia 1996). Numerous types of bunch protectors fabricated with various materials have been tested over the years (Dowson 1976). In our study, date bunch bagging in Tameghza and Elguettar orchards was conducted in mid August, which coincide with the end of kimri and the beginning of bisir stages, to prevent egg laying by *E. ceratoniae* on early maturing dates. Zougari (2015) showed that bagging should not be done at kimri stage to prevent infestation by the date palm mite *Oligonychus afrasiaticus* McGregor (Acari: Tetranychidae). According to Skander Essid (2011), if bunch bagging is applied late in September (ripening period) it will not give the expected results. In the present study, the infestation by the carob moth on date palm trees was significantly lower in plots treated with the bagging technique. Similarly, Skander Essid (2011) revealed that the protection of bunches with mosquito netting bags (100 × 80 cm/ perforations diameter: 0.8 mm2) significantly decreased *E. ceartoniae* infestations on date palm trees in Tunisia. However, bagging requires the destruction of infested and fallen fruits during the cropping season and after harvest to avoid new infestations the following year (Gothilf 1984; Mediouni and Dhouibi 2007). Also, Grissa Lebdi et al. (2020) showed that the carob moth population remained high in oases when bagging technique was used alone.

Integrated Pest Management strategy

In this work, the application of various environmentally-friendly control methods in combination significantly reduced carob moth population levels and fruit damage rate in both oases and years. The infestation rate of fruits at harvest was significantly higher in the control plots as compared to IPM plots, it reached an average of 50.76% on pomegranate and 21.32% on date palm for both studied regions. In Morocco, the carob moth can cause fruit damage reaching 30% in date palm orchards each year (Bouka et al. 2001). Nay and Perring (2008) reported 10–40% yield losses in USA for the same host plant. This pest is also a major field pest of pomegranate in Turkey and Iran, where the mean percentage of infested fruits increased from 33% to more than 80% (Al-Izzi et al. 1985; Mamay and Dağ (2016). In Saudi Arabia, the carob moth caused almost complete destruction of the pomegranate crop (Elsayed and Bazid 2011; Sayed et al. 2015). In recent years, various IPM strategies have been developed and implemented across different world regions to manage pests of economic importance such as *T. absoluta* (Goda et al. 2015; Desneux et al. 2022), *Ceratitis capitata* (Boulahia-Kheder et al. 2012; Elekcioğlu 2019), *C. pomonella* (Polesny 2000; EL Iraqui and Hmimina 2016) and *Rynchophorus ferrugineus* (Faleiroa and Ashok Kumarb 2008). Numerous combinations of control methods have been explored to prevent carob moth infestations and maintain pest populations below economic threshold levels. In Tunisia, Ben Chaaban and Mahjoubi (2019) showed that a mass trapping technique combined with *T. cacoeciae* release provided a 72.9 and 52.8% reduction of carob moth captures, respectively on date palm and on pomegranate trees. In Iran, *Trichogramma* release combined with pomegranate calyx removal provided a 19% reduction of carob moth damage in pomegranate orchards (Rezaei-Azqandi et al. 2015). According to Mirjalili and Poorazizi (2015), the control of carob moth on pomegranates relies on an integrated approach that combines the use of resistant cultivars, sanitation, and *Trichogramma* releases. Alloui-Grizaa et al. (2022) showed that the most effective management against the carob moth in citrus orchards was cultural control combined with mating disruption (500 g/ha of SPLAT EC) and *T. cacoeciae* releases (30,000 Trichogramms/ha), with a reduction rate of the pest population of 62.8%.

Conclusion

To obtain the best results against carob moth, it is essential to use a sequence of cultural (sanitation), biotechnical (mass trapping using Delta pheromone traps), biological (inundative releases of *T. cacoeciae* parasitoids) and physical (date bunch bagging) control methods. These environmentally-friendly methods applied in an efficient and economical manner, can manage this pest and reduce fruit damage, which helps to guarantee sustainable agriculture in Tunisian oases. Date palm and pomegranate, as the dominant crops of oasis zones in Tunisia and the main hosts for *E. ceratoniae*, should be at the centre of intense research and extension work that can lead to the rapid implementation and adoption of this IPM approach. Moreover, a better understanding of the biecology of the carob moth in oasis ecosystems is likely to provide new information on habitat influence or other farming practices that will limit population outbreaks. Finally, oasis farmers will continue to need education and training to keep up with the constant changes in pest management technologies.

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Declarations

Conflict of interest The authors report no conflict of interest.

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