

Pupal mortality of the pine processionary moth *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775) (Lepidoptera, Notodontidae) in Aleppo pine and Atlas cedar forests of northern Algeria

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Abstract

Pupal mortality of the pine processionary moth *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775) (Lepidoptera, Notodontidae) in Aleppo pine and Atlas cedar forests of northern Algeria

The pine processionary moth, *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775), is a significant pest of pine and cedar forests in Southern Europe and North Africa. This study aimed to assess pupal mortality of this pest on two host species, *Cedrus atlantica* and *Pinus halepensis*, in northern Algeria. A total of 1,382 mature larvae were collected in the field and allowed to pupate under laboratory conditions. Mortality caused by parasitism and entomopathogenic fungi was then assessed. Overall mortality ranged from 13.7% to 31.1%, with parasitism contributing 7.0%-11.9% and fungal infections 2.7%-6.3%. Three Diptera parasitoid species were identified: *Exorista segregata* (Rondani, 1859), *Phryxe caudata* (Rondani, 1859) (Diptera, Tachinidae), and *Hemipenthes* sp. (Diptera, Bombyliidae), the latter being recorded for the first time in Algeria. *Exorista segregata* was the most abundant species, accounting for nearly 65% of emerging parasitoids. Additionally, the entomopathogenic fungus *Beauveria bassiana* (Deuteromycotina, Zygomycetes) was identified, indicating potential for biological control despite its low incidence.

Key words: *Thaumetopoea pityocampa*, Pupal mortality, Parasitoid, Entomopathogenic fungus, Biological control, Algeria

Resumen

Mortalidad de las pupas de la procesionaria del pino *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775) (Lepidoptera, Notodontidae) en bosques de pino carrasco y cedro del Atlas en el norte de Argelia

La procesionaria del pino, *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775), es una plaga importante de los bosques de pino y cedro en el sur de Europa y el norte de África. Este estudio tenía como objetivo evaluar la mortalidad de las pupas de esta plaga en dos especies hospedadoras, *Cedrus atlantica* y *Pinus halepensis*, en el norte de Argelia. Se recolectaron en el campo un total de 1.382 larvas maduras, que fueron puestas a pupación bajo condiciones de laboratorio. Posteriormente, se evaluó la mortalidad causada por parasitismo y hongos entomopatógenos. La mortalidad total osciló entre el 13,7% y el 31,1%, con un aporte del parasitismo entre 7,0% y 11,9%, y de infecciones fúngicas entre 2,7% y 6,3%. Se identificaron tres especies de parasitoides del orden Diptera: *Exorista segregata* (Rondani, 1859), *Phryxe caudata* (Rondani, 1859) (Diptera, Tachinidae), y *Hemipenthes* sp. (Diptera, Bombyliidae), siendo esta última registrada por primera vez en Argelia. *Exorista segregata* fue la especie más abundante, representando casi el 65% de los parasitoides emergentes. Además, se identificó el hongo entomopatógeno *Beauveria bassiana* (Deuteromycotina, Zygomycetes), lo que indica un potencial para el control biológico a pesar de su baja incidencia.

Palabras clave: *Thaumetopoea pityocampa*, Mortalidad de las pupas, Parasitoide, Hongo entomopatógeno, Control biológico, Argelia

Resum

Mortalitat de les crisàlides de la processionària del pi *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775) (Lepidoptera, Notodontidae) als boscos de pi blanc i cedre de l'Atlas al nord d'Algèria

La processionària del pi, *Thaumetopoea pityocampa* (Denis & Schiffemüller, 1775), és una plaga important dels boscos de pi i cedre al sud d'Europa i el nord d'Àfrica. Aquest estudi tenia com a objectiu avaluar la mortalitat de les crisàlides d'aquesta plaga en dues espècies hostes, *Cedrus atlantica* i *Pinus halepensis*, al nord d'Algèria. Un total de 1.382 larves madures es van recollir al camp i se'ls va permetre pupar en condicions de laboratori. A continuació es va avaluar la mortalitat causada pel parasitisme i els fongs entomopàtogens. La mortalitat total va oscil·lar entre el 13,7% i el 31,1%, amb el parasitisme contribuint amb el 7,0%-11,9% i les infeccions per fongs entre 2,7%-6,3%. Es van identificar tres espècies parasitoides de l'ordre Diptera: *Exorista segregata* (Rondani, 1859), *Phryxe caudata* (Rondani, 1859) (Diptera, Tachinidae), i *Hemipenthes* sp. (Diptera, Bombyliidae), aquest últim es registra per primera vegada a Algèria. *Exorista segregata* va ser l'espècie més abundant, representant gairebé el 65% dels parasitoides emergents. A més, es va identificar el fong entomopàtogen *Beauveria bassiana* (Deuteromycotina, Zygomycetes), que indica un potencial per al control biològic malgrat la seva baixa incidència.

Paraules clau: *Thaumetopoea pityocampa*, Mortalitat de les crisàlides, Parasitoide, Fong entomopàtogen, Control biològic, Algèria

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Introduction

The pine processionary moth (PPM), *Thaumetopoea pityocampa* (Denis & Schiffermüller, 1775) (Lepidoptera, Notodontidae), is considered one of the most important forest pests in the Mediterranean Basin and other southern European regions (Palacio et al 2012, Jacquet et al 2013, Li et al 2015, Campôa et al 2021, Camarero et al 2022). This pest is oligophagous on *Cedrus* and *Pinus* species, occurring in both native and artificial stands (Ayache et al 2021, Rahim et al 2021a, Bouzar-Essaidi et al 2023).

Thaumetopoea pityocampa has a univoltine life cycle. Adults emerge, mate, and lay eggs in a single clutch on pine needles or the underside of cedar twigs, in July at colder sites and in August at warmer sites. Each egg batch contains, on average in northern Algeria, 220 eggs, covered with protective scales produced by the female (El Mokhefi et al 2021). These egg batches are small, inconspicuous, and difficult to detect in the tree canopy.

Embryonic development lasts 30-45 days; the larvae live in aggregations and form a conspicuous white nest at the top of the trees, where they develop until spring. The winter nests built by late-instar larvae are easily detected even at low population levels. Mature larvae leave the tree in a single-file, head-to-tail procession in search of suitable soil sites for pupation. Some pupae undergo prolonged diapause lasting 1-6 years, which is conditioned by the surrounding environment (Zamoum 1998).

Currently, the latitudinal and altitudinal expansion of the PPM's range have been attributed to climate warming (Roques 2015, Bourougaaoui et al 2021, Rossi et al 2025). In Algeria, outbreaks occur in Aleppo pine *Pinus halepensis* (Miller, 1768) forests in semi-arid areas and Atlas cedar *Cedrus atlantica* (Manetti, 1841) forests in sub-humid elevation area (El Mokhefi et al 2016). The expansion of this species in Algeria has been favored by the large-scale afforestation program known as the Barrage Vert, consisting of Aleppo pine plantations aimed at combating desertification along the Saharan Atlas (Zamoum 1998). These outbreaks cause significant radial growth losses, lead to tree dieback after repeated defoliation, and increase susceptibility to secondary pests and pathogen attacks (Sbabdji and Kadik 2011, Jacquet et al 2012). Additionally, this moth can affect humans and animals due to the release of microscopic urticating hairs (setae) from third instar larvae, which cause respiratory problems, skin lesions of varying severity, and allergic reactions (Battisti et al 2024).

Natural enemies (i.e., predators, parasitoids, and pathogens) play a crucial role in regulating many harmful insect pests (e.g., Rahim et al 2016, García et al 2021, Sebti et al 2022). Throughout the Mediterranean region, many natural antagonists may contribute to controlling the pine processionary moth. These include parasitoids (Ayache et al 2021, Mirchev et al 2021), pathogens (Dannon et al 2020, Topkara et al 2022), insectivorous birds such as the great tit *Parus major* (Barbaro et al 2013), tettiioniids (Hódar et al 2013), and ants (Way et al 1999). These natural enemies attack all life stages of the pest, from embryos in eggs, to larvae at any instar stage, during pupation, and as adults (Battisti et al 2015a, 2021b). Given the recent increase in the frequency of *T. pityocampa* outbreaks in multiple pine and cedar forests in Algeria, and the potential for future outbreaks due to climate warming (Robinet et al 2013, Bourougaaoui et al 2024), our objectives are: (1) to identify the natural enemies developing from pupae of *T. pityocampa* pupae in Atlas cedar and Aleppo pine forests of northern Algeria, and (2) to determine the contribution of parasitoid diversity to pupal mortality. The data collected may suggest opportunities for biological control in these fragile forest ecosystems.

Materials and Methods

Sampling sites

The study was conducted in 2020 in two plantation forests located in northern Algeria: Halouan and Tadjenanet (table 1, fig. 1). The distance between the two forest sites is about 200 km. The first site, Halouan, is a pure Atlas cedar plantation (35 years old trees), located in Djurdjura National Park, covering an area of almost 8,000 ha. The locality has a subhumid bioclimate, with average temperatures of 3 °C in winter and 20 °C in summer, and an average annual rainfall of 1,300 mm. The second site, Tadjenanet, is a pure Aleppo pine plantation (30 years old trees), located in the Mila region and covering an area of 300 ha. This area has a semi-arid bioclimate, characterized by average annual temperatures of 9 °C in winter and 28 °C in summer, and an average annual rainfall of 400 mm.

Table 1. Main environmental characteristics of the studied sites.

Tabla 1. Principales características ambientales de las áreas estudiadas.

Site	Latitude(N)	Longitude(E)	Elevation(m)	Topog. Orientation	Slope(%)	Host plant	Tree height(m)
Halouan	36° 27'	3° 56'	1233	Northeast	13.2	<i>Cedrus atlantica</i>	3-8
Tadjenanet	36° 07'	6° 00'	842	Southeast	2.1	<i>Pinus halepensis</i>	2-6

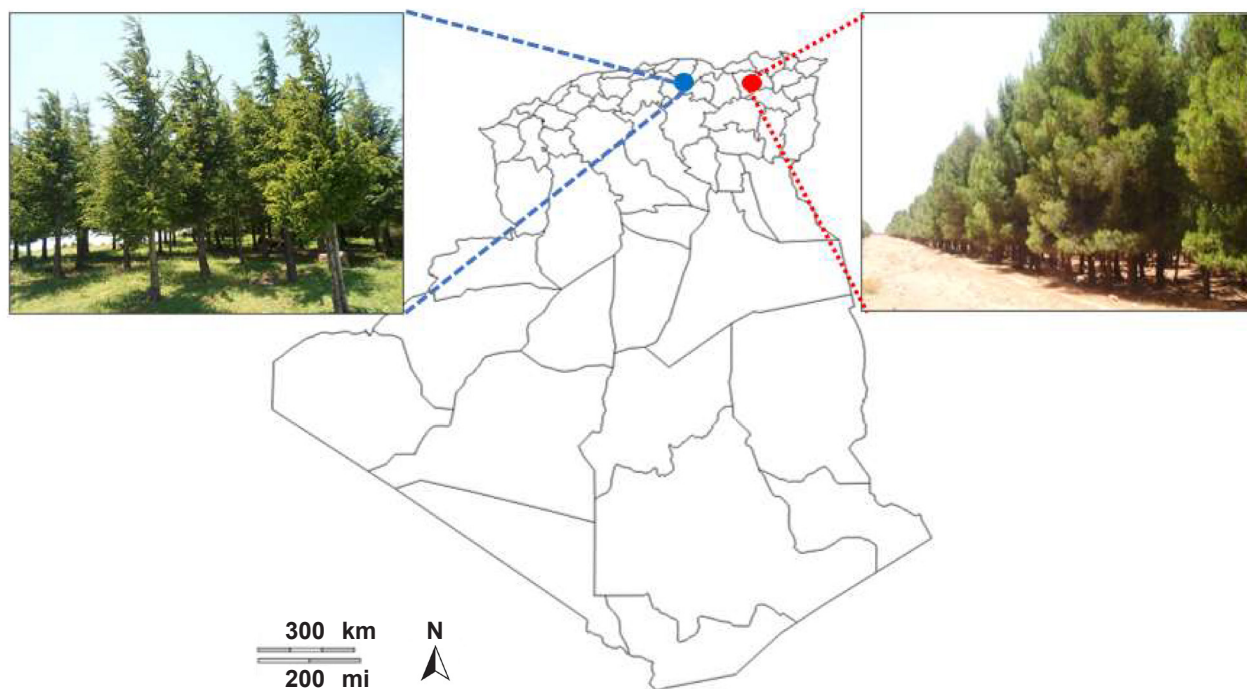


Fig. 1. Map of Algeria showing the locations of the two forest sites: blue represents the Atlas cedar forest of Halouan; red represents the Aleppo pine forest of Tadjenayet.

Fig. 1. Mapa de Argelia que muestra la ubicación de los dos bosques: en azul, el bosque de cedro del Atlas de Halouan, en rojo el bosque de pino carrasco de Tadjenayet.

Population density of *T. pityocampa*

The winter nests made by *T. pityocampa* larvae were counted. *Thaumetopoea pityocampa* density was estimated as the mean number of winter nests per tree. Nest counts were conducted at each site on 35 trees along a linear (about 300 m long) (Jactel et al 2006). Trees were visually inspected in all directions beneath the canopy for the presence of nests. This survey was conducted in January, when nests are most visible (Colacci 2018).

Sampling of larvae of *T. pityocampa* and collection of parasitoids

At each site, mature larvae (fifth instar) of *T. pityocampa* actively searching for pupation sites in the soil were collected weekly from January to March. This period corresponds to the pupation procession and the beginning of the pupation phase of the pest. Mature larvae were randomly collected along access roads at forest margins and up to 100 meters into the forest, depending on population density. Collection areas spanned approximately 5-6 ha. In total, 1,382 larvae were collected, either with or without visible evidence of parasitism. Field-collected larvae were reared in groups of 50 individuals in cylindrical plastic containers (20×20×25 cm) filled with soil, covered with 1 mm nylon tulle, and maintained at 28±2 °C until parasitoid emergence, host death, or pupation. Pupal cocoons were carefully removed, and pupae were placed individually, without soil, into labeled glass tubes (70 mm×9 mm), sealed with cotton plugs, and stored in a dark room at 26±2 °C until emergence of parasitoids or adult moths.

Statistical analysis

Parasitism percentage was calculated as the number of insects from which parasitoids emerged divided by the total number of insects in the sample. To compare *T. pityocampa* density (nests per tree) and pupal mortality between sites, a one-way ANOVA test was performed after testing for normality and homoscedasticity. The Chi-square (χ^2) test was used to compare the frequency of parasitoid species between sites. All statistical analyses were performed using SPSS v25 (IBM Corp., Armonk, N.Y., USA, 2017).

Table 2. Population density of *T. pityocampa* (nests/tree) at the two study sites.**Tabla 2.** Densidad de población de *T. pityocampa* (nidos/árbol) en de las dos áreas estudiadas.

Site	Means ($\pm$ SD)	Min-Max
Halouan	1.74 $\pm$ 0.78	0-3
Tadjenanet	6.09 $\pm$ 1.29	2-8

Table 3. Survival and mortality of *T. pityocampa* pupating larvae.**Tabla 3.** Supervivencia y mortalidad de las larvas en pupación de *T. pityocampa*.

Site	N total	Emerged adults % (N)	Pathogens % (N)	Parasitoids % (N)	Unknown % (N)	Total mortality % (N)
Tadjenanet	969	69.2 (671)	6.3 (61)	11.9 (115)	12.6 (122)	30.8 (298)
Halouan	413	78.7 (325)	2.7 (11)	7.0 (29)	11.6 (48)	21.3 (88)
Overall	1382	72.1 (996)	5.2 (72)	10.4 (144)	12.3 (170)	27.9 (386)

Results

Population density

The population density of *T. pityocampa* (mean number of nests per tree) varied significantly between the two study sites ($F_{1,68} = 289.87$, $p < 0.01$). The mean ($\pm$ SD) density of winter nests per tree was notably higher in the Aleppo pine forest of Tadjenanet (6.09 $\pm$ 1.29) compared to the cedar forest of Halouan (1.74 $\pm$ 0.78) (table 2). These findings highlight clear differences in population levels, with the pine stands of Tadjenanet experiencing significantly higher densities, while the cedar stands of Halouan maintained a consistently low population density.

Mortality factors

The overall mortality rate of *T. pityocampa* larvae during pupation was 21.3% in the Halouan cedar forest and 30.8% in the Tadjenanet pine forest, with a highly significant difference ($F_{1,25} = 16.59$, $p < 0.01$) (table 3). Mortality of *T. pityocampa* due to parasitoids was 11.9% in Tadjenanet and 7.0% in Halouan, with highly significant differences between the two sites ($F_{1,25} = 23.82$, $p < 0.01$). Fungal infection rates also differed between the two sites ($F_{1,25} = 15.28$, $p < 0.01$), being higher in Tadjenanet, 6.3%, than in Halouan, 2.7%. Mortality from undetermined causes, not attributable to pathogens or parasitoids, was 11.6% and 12.6% in Halouan and Tadjenanet, respectively. No difference was found between sites for this category.

Parasitoid complex: species composition and relative abundance

During the study, *T. pityocampa* pupae were parasitized by three species: *Exorista segregata*, *Phryxe caudata*, and *Hemipenthes* sp. The frequency of parasitoid species did not differ significantly between the two sites ($\chi^2 = 5.018$, $p = 0.658$). Table 4 shows the relative abundance of parasitoids emerging from *T. pityocampa* pupae. Tachinid flies were predominant in both sites, comprising 91.7% of all emerging parasitoids (132 individuals). *Exorista segregata* was the most prevalent, with relative abundance ranging from 58.3% to 72.4%, followed by *P. caudata*, contributing 27.6% at Halouan and 31.3% at Tadjenanet. *Hemipenthes* sp. was recorded only in Tadjenanet, representing 1.7% of parasitoids. Additionally, 8.7% of parasitoid pupae did not yield adults and remained unidentified.

Discussion

The difference in *T. pityocampa* density observed between Tadjenanet and Halouan aligns with findings from other studies that emphasize the influence of climate on population levels. Buffo et al (2007) observed similar patterns, noting that warmer, drier climates support higher densities of *T. pityocampa*, as these conditions favor larval development and

Table 4. Insect parasitoids of *T. pityocampa* and their relative abundance.

Tabla 4. Insectos parasitoides de *T. pityocampa* y su abundancia relativa.

Site	Parasitoid species	Emergence period	N	Relative abundance %	Mortality %
Tadjenanet	<i>Exorista segregata</i>	June-September	67	58.3	9.6
	<i>Phryxe caudata</i>	June-September	36	31.3	3.7
	<i>Hemipenthes</i> sp.	August	2	1.73	0.2
	Unidentified diptera	-	10	8.7	1.0
Halouan	<i>Exorista segregata</i>	June-September	21	72.4	5.1
	<i>Phryxe caudata</i>	June-September	8	27.6	1.9

increase host tree susceptibility. Additionally, Zamoum (1988) reported that *T. pityocampa* populations tend to expand and reach higher densities in semi-arid regions, where drought-stressed host species such as Aleppo pine are more vulnerable to infestation. In contrast, humid climates with higher rainfall and lower temperatures, like those in Halouan, often limit *T. pityocampa* densities. Régolini et al (2014) observed that denser, wetter forests have lower nest densities, as higher moisture levels and cooler temperatures slow larval development and reduce survival rates. These environmental constraints, along with the host characteristics of Atlas cedar, may explain the reduced nest density in Halouan. This comparative analysis highlights that warmer, drier conditions, particularly in Aleppo pine forests, provide a more favorable environment for *T. pityocampa*, as demonstrated by the higher nest density in Tadjenanet.

The highest mortality caused by parasitoids in the Aleppo pine forest of Tadjenanet, the site with the highest PPM abundance density, could be interpreted as a simple density-dependent mechanism (increased probability of parasitoids encountering the larvae). According to Hall et al (2019), the effectiveness of parasitoids depends on the population density of insect pests, with the highest percentages of parasitism recorded during outbreaks. In our study, the Aleppo pine forest of Tadjenanet exhibited clear signs of an outbreak phase, characterized by high PPM density (6.09 ± 1.29 nests/tree). In contrast, the cedar forest of Haloun, with a much lower density (1.74 ± 0.78 nests/tree), represented a population in equilibrium. This variation in population dynamics likely influenced the activity and effectiveness of natural enemies, as parasitoids are known to respond to higher host densities during outbreak conditions. Lower and moderate levels of parasitism in several insect herbivores are commonly observed during non-outbreak periods (Quayle et al 2003, Zovi et al 2006, Paritsis et al 2012, Maguire et al 2015, Rahim et al 2016, Hall et al 2019).

In our study, total parasitism rates ranged from 7.0% to 11.9%, suggesting that parasitoids contribute relatively little to *T. pityocampa* mortality. These findings contrast with the much higher parasitism rate of 43.9% reported by Zamoum et al (2007) in the sub-Saharan region of Algeria. This discrepancy could be attributed to several factors, including differences in the parasitoid community, local ecological conditions, or pest dynamics in the two regions. For example, the sub-Saharan region may have a more favorable environment for parasitoid survival and reproduction, leading to higher parasitism rates during *T. pityocampa* outbreaks. Additionally, parasitoid species composition and host availability could vary between sites, influencing the effectiveness of parasitism. Furthermore, differences in the timing of parasitoid activity relative to *T. pityocampa* life stages may also explain the observed variation in parasitism levels. These observations emphasize the importance of considering population dynamics, including gradation phases, when evaluating the role of natural enemies in regulating PPM populations across different regions.

The Tachinidae family (Diptera) plays a crucial role among parasitoids, contributing significantly to the control of economically important insect pests. Tachinid flies predominantly parasitize late-instar larvae and pupae, effectively suppressing various lepidopteran pest populations (Rahim 2016, Hammami et al 2019, Ciner et al 2025, Cingolani et al 2025).

Among the tachinid species, *E. segregata* is a highly polyphagous and polyvoltine parasitoid of Lepidoptera. This species, widely distributed across Mediterranean regions, is particularly noted for parasitizing *Thaumetopoea* species. It has been reported attacking *T. ispartaensis* (Avci and Kara 2002), *T. pityocampa* (Aytar and Turgut 2021, Hubenov 2025), *T. wilkinsoni* (Erkaya 2020, Aytar and Turgut 2021), and *T. solitaria* (Halperin 1990). In Algeria, *E. segregata* has also been found parasitizing the cedar processionary moth *T. bonjeani* (Rahim 2016) and the spongy moth *Lymantria dispar* (Mecellem and Chakali 2021).

Phryxe caudata is another critical tachinid parasitoid, commonly observed in Mediterranean countries as a key parasitoid of *T. pityocampa* (Robinet et al 2012, Battisti et al 2015b, Bonsignore et al 2015, Zamoum et al 2017, De Boer and Harvey 2020). This parasitoid has two generations per year: the first emerging in spring from mature larvae and the second in summer-autumn from pupae (Buxton 1990). *Phryxe caudata* has been documented parasitizing *T. ispartaensis* (Avci and Kara 2002) and *T. wilkinsoni* (Aytar and Turgut 2021).

The genus *Hemipenthes*, known to parasitize *T. pityocampa* in Europe, was recorded for the first time in Algeria. *Hemipenthes* species, including *H. velutina* and *H. morio* (Tarasco et al 2015, Rubin 2020), were previously reported as the main parasitoids of *T. pityocampa* in Europe. Our study marks the first record of *Hemipenthes* sp. parasitizing *T. pityocampa* in Algeria.

Additionally, *Beauveria* species, particularly *B. bassiana*, were identified as significant contributors to *T. pityocampa* pupal mortality. *Beauveria* species infect a wide range of insect pests globally and have been documented to attack larvae and pupae of several *Thaumetopoea* species (Mirchev et al 2012, Battisti et al 2020, Yanar et al 2023, Yaman and Güvendik 2024, Koç et al 2025). In Italy, however, its effectiveness against *T. pityocampa* pupae has been reported as relatively low, with a reduction of about 10% (Tarasco et al 2016), while Battisti et al (2015a) found a higher efficacy of approximately 20% in southern Algeria. Compared to these studies, the current findings suggest a comparable or slightly enhanced impact of *B. bassiana* under local conditions, indicating that regional environmental factors and strain variability may influence its effectiveness (Zamora-Avilés et al 2024).

Conclusion

The diversity of natural enemies associated with *T. pityocampa* in Algeria appears relatively low, with only three parasitoid species and one fungal species identified. To gain a better understanding of the factors influencing the population fluctuations of this pest in pine and cedar forests, future research should examine the combined effects of parasitoids, pathogens, and abiotic conditions on *T. pityocampa* population dynamics. Investigating the synergistic potential of biological control agents, particularly *B. bassiana*, in integrated pest management programs could offer sustainable solutions. Additionally, long-term monitoring across climate zones may provide valuable insight into how climate change could affect influence pest dynamics, potentially leading to more tailored and effective pest management approaches in forest ecosystems.

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