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Review article

A review on biology and possible management strategies of tomato leaf miner, *Tuta absoluta* (Meyrick), Lepidoptera: Gelechiidae in Nepal

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ABSTRACT

Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae), Tomato Leaf Miner (TLM) moth, is one of the notorious oligophagous pests of solanaceous crops that mines primarily on mesophyll of leaves as well bore tomato fruits. In Nepal, *T. absoluta, the pest that has a potential to create loss up to 100%,* was detected in 2016 in a commercial tomato farm at Kathmandu. So, the farmers and researchers must heed for effective management contrivance to improve the yield of tomato in Nepal. The devastating nature of *T. absoluta* causes its unusual proliferation so that it needs dire study of its host range, potential damage and sustainable management strategies. We discussed the data and information on *T. absoluta* available in several research papers comprehensively and provided succinct information on occurrence of *T. absoluta* in the world, its biology, life cycle, host plants, yield loss due to *T. absoluta* and several novel control tactics which helps farmers, researchers, policy makers to sustainably rise the tomato production in Nepal as well as in global context to attain food security. Sustainable pest management strategies such as Integrated Pests Management (IPM) approaches incorporating and prioritizing biological control methods with usage of chemical pesticides with less toxic active ingredient can be encouraged to the farmers for controlling the pests sustainably.

1. Introduction

Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae), Tomato Leaf Miner (TLM) is one of the devastating pest of tomato which is of great concern around the globe. *T. absoluta* is recognized by its other names as South American tomato moth, South American tomato pinworm in South America, tomato borer, *Phthorimaea absoluta* in Peru, *Gnori-moschema absoluta*, *Scrobipalp*ula *absoluta*, and *Scrobipalpuloides absoluta* around the globe [1,2]. It has a wide range of hosts from various crop families like Fabaceae, Amaranthaceae, Convolvulaceae, and Malvaceae [3]. Tomato (*Lycopersicon esculentum* L.) appear to be the major host of *T. absoluta* among a variety of Solanaceous species. Tomato production is hampered by a number of biotic and abiotic constraints [4] and *T. absoluta* is the major biotic constraint in the production of tomato both in green house and open field condition [5]. According to Desneux et al. [6],

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T. absoluta has spread and increased its range mostly through agricultural trade of tomato fruits.

It is a holometabolous insect with a lifecycle of 26–75 days [6,7]. The complete development of the insect takes 500° days (measure of heat accumulation based on the daily highest and lowest temperatures). They become active after dusk, and adults usually hide in throughout the day, while they extraordinarily move in early morning [2]. The adult of *T. absoluta*, which is greyish in color, measures about 5–7 mm in length. It has a wingspan of 8–10 mm, with dark patches in the forewings. Due to its vigorous reproductive potential, it produces 10–12 generations per year [8]. The pest is mostly nocturnal, and adults normally stay hidden throughout the day. Adults exhibit more morning-crepuscular activity, distributing among crops by flying [6]. Its larvae create inter-laminar mines causing leaf necrosis and early defoliation, which lead to reduced photosynthetic production. The irregular mines gradually unite and create galleries as a result of the larvae's continuous feeding [9]. These mines are full of larvae and deposits of excreta near the external opening [10]. The leaves appear to be burnt after strong infestations. Puncture marks, irregular shape, exit holes, rot due to secondary infective agents, and frass are all common signs and symptoms of *T. absoluta* damage. All portions of the plant are edible to mature larvae (third to fourth instar) [4]. Indirect damage occurs when fungi and bacteria enter pre-infested leaves, buds, stems, and fruits.

This pest was reported for the first time in Nepal in 2016 at Kavresthali, Kathmandu with causing a yield loss of 80%–100% [11]. The use of plastic tunnel houses with pest exclusion nets is gradually gaining popularity. Management of *T. absoluta* relies on a variety of tactics that include both preventive and curative approaches. Strict phytosanitary inspections of propagation material, the installation of infrastructure that provides mechanical protection, and close monitoring of pest status through crop surveys and/or pheromone traps are all examples of preventive methods [12–14]. However, rigorous studies regarding the natural enemies and other cultural methods are still lacking. This paper aims to provide insights on the biology and the possible management strategies of *T. absoluta* to guide farmer and researcher adopt appropriate techniques for effective and sustainable management of tomato leaf miner.

2. Methodology

A systematic approach was exercised to collect the information on *T. absoluta.* The use of electronic sources such as Google Scholar, PubMed, Scopus (Elsevier), Web of Science, Semantic scholar, Academia and other relevant websites were used to search for available literatures. For the grey literatures, we retrieved information from Nepal Agricultural Research Council (NARC) and other related websites. We mainly incorporated the management strategies of deleterious pest, *T. absoluta.*

3. Occurrence of *Tuta absoluta*

3.1. Occurrence in the world

It has been a key pest of tomato in South America for more than 50 years [7]. *T. absoluta* was first discovered in Huancayo, Peru in 1917 [15]. It is believed to have been introduced accidently to eastern Spain in 2006, from where it spread rapidly into several Mediterranean and European countries [16]. *T. absoluta* can easily adapt in varied agro-ecological condition which favors for the rapid multiplication of pest [8]. As per reports of [17,18], it is invading the African region at an alarming rate. Since its first report in Morocco and Algeria in 2008, *T. absoluta* has spread throughout Africa [19]. *T. absoluta* is reported in many African countries causing

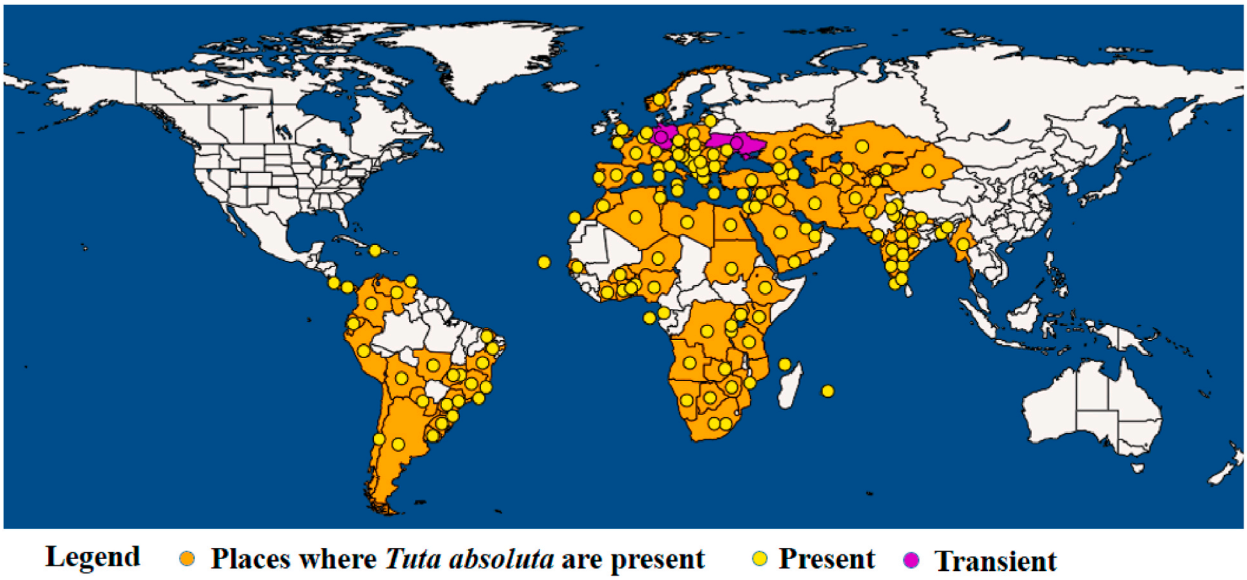

Fig. 1. Current worldwide *Tuta absoluta* distribution map (as of October 2022). Source [26].

catastrophic damage in Ethiopia, Kenya and Sudan showing alarm alert of heavy loss [20,21]. Asia has also experienced a rapid spread since its first detection in Turkey (2009) [22]. It reached western and eastern India in 2014 and 2017 respectively [23]. It has been detected in many Asian countries like Iran, Bangladesh, Iraq, Israel, Japan, Jordan, Kyrgyzstan, Lebanon, Nepal, Qatar, Saudi Arabia, Syria, Tajikistan, Turkey, United Arab Emirates, Uzbekistan and Yemen where it has been officially reported [24]. Fig. 1 shows current worldwide distribution of *T. absoluta.* This pest is not known to occur in the United States currently [25].

3.2. Occurrence in Nepal

T. absoluta is suspected to have been introduced in Nepal through India [27]. Tomato imports from India are the most potential mode of entry for this pest. Pest identification was done by studying its external morphology and male genitalia in Entomology Division, Nepal Agricultural Research Council (NARC). It was later verified by the Division of Entomology, Indian Agricultural Research Institute (IARI), New Delhi, India. A survey carried out by NARC from May 16, 2016 to June 10, 2016 identified and confirmed the presence of the pest in 14 locations of the five districts of Nepal [11]. Fig. 2 shows the districts of Nepal where *T. absoluta* was detected in 2018. The survey study showed more than 50% infestation in tomato by *T. absoluta* in Tarakeshwor-9 of Kathmandu district and Kamalbinayak-4 of Bhaktapur District [11]. Ugrachandi Nala-2 and Panchakhal of Kavrepalanchowk district were among the first places to face high damage to tomato crop due to this pest [11]. The loss of tomato crop during the first incidence and damage in 2016 was approximated to be 57.51% in the Kavrepalanchowk district alone [28].

4. Biology of *Tuta absoluta*

4.1. Egg

Female adults lay 250 to 300 eggs on the underside of leaves of the host plants singly or less frequently grouped [18,30–32]. It is rare for *T. absoluta* to lay eggs in fruits [33]. The egg stage lasts for about 7 days; however, time may elongate with lower temperature. The eggs are oval-cylindrical and are approximately 0.35 mm long. Egg color varies from oyster white to yellow. The eggs darken at the embryonic phase and become black near the hatching stage [34].

4.2. Larva

The larvae are green in colour. When larvae shed their skin, their body color changes to whitish for a few hours [35]. The stage lasts for about 11 days under optimum environmental conditions. Transitioning between instars, they mine vigorously to grow (0.9 mm-first instar, to 7.5 mm-fourth instar). Until the food is available the larvae are unlikely to enter diapause. The mature larvae fall and penetrate the soil where they produce a thin, silky cocoon that turns into pre-pupae and then pupae [7].

4.3. Pupa

Pre-pupa is a transition stage between larva and pupa, which is lighter than the larva. They develop a distinguishing pink coloration

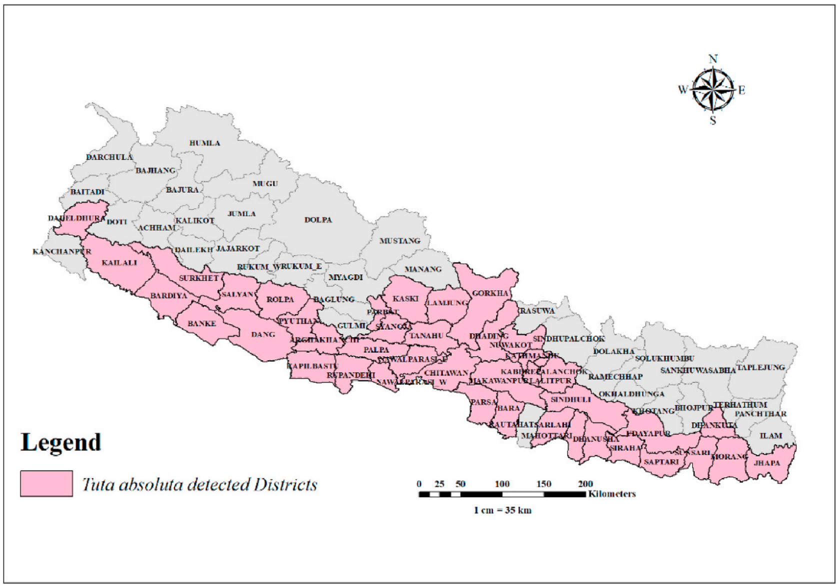

Fig. 2. Districts of Nepal showing distribution and detection of *T. absoluta* as of 2018. Source: Map prepared from data available at [27,29].

on the dorsal surface. The larvae build silk cocoons on leaflets or in the soil according to the habitat after leaving the mines. Pre-pupae do not form cocoons when pupation occurs in mines [34].

Pupation mostly happens in the soil whereas occasionally in stems, dried leaves, or often within mines [31]. In the soil, pupae are protected from chemicals and high temperatures with strong sunshine on days [18,32]. Fourth instars form a silken cocoon inside which pupae (brown in color and around 6 mm long) are formed. At the initial stage of pupation, pupae are greenish in color and turn into chestnut brown which eventually changes its color to dark brown. The pupal stage lasts for five days.

4.4. Adult

Adults are 5–7 mm in length. They have silverish-grey scales, filiform antennae, alternating light or dark segments, and recurved labial palps which are well developed [34]. Adults are nocturnal and hide between leaves during the daytime and have intense activity in the morning. Black spots are found on anterior wings and females are bigger than male [6]. Females live for 10–15 days whereas males live for 6–7 days.

4.5. Total lifecycle of T. absoluta

T. absoluta is the holometabolous insect with egg, larva, pupa and adult stage during their life [20]. The life cycle completes within 30–35 days. It develops 10–12 generations/year in greenhouse conditions [6]. The climatic conditions have a significant impact on the growth, development, and invasion of this pest. These pests remain viable during the winter season, and during the hot season, they move to open areas [36]. Fig. 3 shows life cycle of *T. absoluta.* Mating and egg laying occurs at night time. *T. absoluta* needs a temperature of 30 °C for optimum growth, while the upper and lower thresholds of development are 34.6 °C and 14 °C, respectively [37].

5. Host plants of *T. absoluta*

Information on the biology of *T. absoluta* suggest its primary host is tomato. While *T. absoluta* mainly prefers species belonging to Solanaceae family, some other plants *Phaseolus vulgaris* L. and *Peruviana* L. also manifest *T. absoluta* infestation [39]. The main host, wild hosts and minor hosts of *T. absoluta* are listed in Table 1. Its wide host range allow the insect to continue its life cycle even on the seasons when tomatoes are not cultivated [40]. Studies conducted by Smith et al. [41] showed that weeds such as *Datura stramonium* L. and *Solanum. nigrum* L. have shown suitability on thriving the *T. absoluta*, which suggests that weed management can be a viable option in controlling the devastating pest. Suitability of the insect on these plants mainly depends on the preference exhibited by the insect to oviposit, and the nutritional requirement supplied by the leaves fed during the larval stage [39].

5.1. Entry and pathways of T. absoluta

Natural dispersal such as wind also spread this invasive pest. They spread through the infested tomatoes imported from other

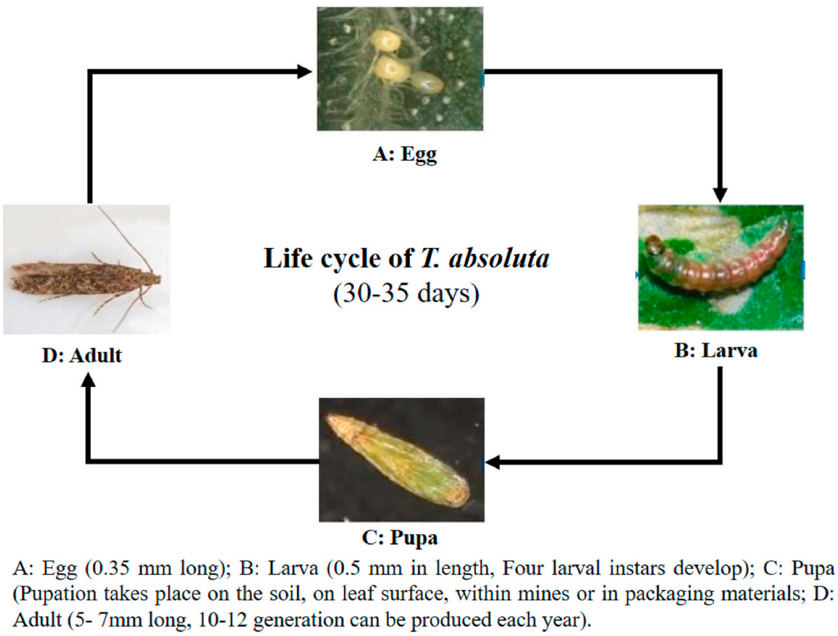

Fig. 3. Life cycle of *T. absoluta,* Modified from [38].

Table 1
Host plants of *T. absoluta*.

Host plants of *T. absoluta*	References
Main host:	
Tomato (*Lycopersicon esculentum* L.)	[6]
Tobacco (*Nicotiana tabacum* L.)	[42]
Wild hosts:	
Alfalfa (*Medicogo sativa* L)	[43]
Amaranthus spinosus L.	[44]
Blitum bonus-henricus (L.) Rchb.	
Solanum coagulans Forssk.	
Datura ferox L.	[42]
Datura stramonium L	[42]
Datura ferox L.	[20,45–47]
Datura quercifolia Kunth	
Lycium chilense Bertero	[42]
Lycopersicon hirsutum Humb. & Bonpl.	[48]
Oxybasis rubra (L.) S. Fuentes, Uotila & Borsch	[44]
Physalis angulate L.	[48]
Solanum aethiopicum L.	
S. americanum Mill.	
S. elaeagnifolium Cav.	[49]
S. lyratum Thumberg	[42]
S. macrocarpon L.	
S. nigrum L.	
S. puberulum Nuttal ex Seemann	
S. scabrum Mill.	
S. sarrachoides (Sendtner)	[50]
S. villosum Mill.	[20,45–47]
S. bonariense L	
S. habrochaites S. Knapp	
S. sisymbriifolium L.	
Tree tobacco (*Nicotiana glauca* Graham)	
Xanthium strumarium L.	[50]
Minor Host	
Potato (*S. tuberosum* L.)	[2,20,45]
Sweet pepper (*S. muricatum* L.)	
Eggplant (*S. melongena* L.)	
Tobacco (*Nicotiana tabacum* L.)	
Cape gooseberry (*Physalis peruviana* L.)	
Pepinodulce (*S. muricatum* Aiton)	
Peppers (*Capsicum annuum* L.)	

countries [51]. They might also enter while importing planting materials, boxes, crates, and pallets transported from the countries where pests are prevalent [17]. The pathways of *T. absoluta* spread are discussed below:

Seedlings: The probability of pest survival is high during the transportation or storage of seedlings since the plants are transported alive with leaves.

Tomato fruits: The probability of survival of larvae in fresh tomato fruits transport is high. Fruits intended to be traded should have no signs of insect damage.

Production facilities: If the pests arrive in the late larval stage or as pupa, they can develop into a moth at the production facilities. So, the production facilities like packing and distribution centers are at high risk of pest spread.

Farm equipment's and vehicles: Farm equipment's from infested areas and transport vehicles should be kept clean. Importing countries should ensure that the crates used in transportation have been sanitized. Packaging in contact with infested fruits should be disposed of properly.

Table 2
Yield losses of tomato due to *T. absoluta* in different parts of the world.

Country	Losses	References
Ethiopia	60.08%–82.31%	[53]
Tunisia	11%–43%,	[54]
Egypt	Up to 100%	[9]
Sudan	80%–100%	[55]
Angola	84%–100%	[56]
Zambia	90%	[57]
Tanzania	90% and 100%	[58]

6. Yield losses due to *Tuta absoluta*

Tomato Leaf Miner is one of the most devastating pests of tomato in greenhouse, glasshouse and field conditions. Its feeding habit makes it difficult to detect it in the early infestation period. Infestation causes significant yield and quality loss of tomatoes and other crops. Yield loss affects the farmers directly due to reduction in the marketable yield and indirectly through high production costs after pest intervention. Variable yield losses (Table 2) can be seen from 11% that can reach as high as 100%, so its appropriate management is must. Damages caused by *T. absoluta* is due to direct feeding on plant parts like leaves, flowers (calyx and corolla), stems and fruits (immature and ripened) accompanied by secondary infection due to entry of pathogens from the wound created by *T. absoluta* [52]

7. Management strategies of *T. absoluta*

T. absoluta has emerged as threatening agricultural pest in the modern agriculture system. It results in huge damage to tomato fields. In these times, when the sustainability of any activity is being reconsidered, pest management must follow sustainability policies. Unsustainable and over-use of chemical pest control methods could develop pesticide resistance among the pest population. Farmers respond with a greater dose of pesticides when they find the use of the same pesticides ineffective. The heavy use of hazardous chemicals has been causing serious health issues in humans, environment, and non-targeted animals.

To act against this disastrous situation, farming needs to be incorporated with Integrated Pest Management (IPM). IPM incorporates the policy of pest management instead of the traditional practices towards pest management. It approves methods like soil solarization, use of resistant varieties, insect trapping, introducing natural enemies, and using botanicals and bio-control agents [59]. Not all of these methods are perfectly efficacious, but their integrated adoption is a much safer way of agricultural production.

7.1. Cultural measures

It is the approach that accounts for manipulating the environmental condition that favor for survival, growth and multiplication of *T. absoluta* like intercropping, crop rotation, planting trap crops, manipulation of planting time of tomato, boundary cropping, mixed cropping, and so on. Tomatoes can benefit from being interplanted with coriander (*Coriadrum sativum* L.) and gallant soldier (*Galinsoga parviflora* L.) since it lowers insect densities and strengthens natural enemies [60]. The farmland should be free from the crop residue and debris of last season. Such residues can be either buried beneath the earth or destroyed by burning. In hot regions, soil solarization can be done to destroy the pupating insects in soil [61]. Mono cropping of the tomato should be avoided and crop rotation with the non-host crops such as the crucifers should be practiced [62]. Fine screening nets can be used to surround the fields. The greenhouse is an appropriate setting to maintain the bio-dynamics of the confined agro-ecology. Moreover, 'Push and Pull' strategies can be utilized to maintain the delicate balance between the populations of natural predators and the pest. Other good agricultural practices such as proper tillage, timely irrigation, and judicial application of fertilizers can ensure minimum pest attack by *T. absoluta* [62].

7.2. Physical measures

This approach of pest management is concerned with preventing or decreasing the attack of pest to the plant. Megido et al. [42] suggested that the use of virgin females as lures is more convenient and economical as compared to light trapping. Delta traps with appropriate lure and a sticky portion inside the trap is used to trap the pest. Instead of a sticky portion, these delta traps may also have a detachable lining [63]. The trap height should be set around the height of the plant with a relatively higher infestation [42]. According to Kadel et al. [64], *T. absoluta* can recognize different colors and respond accordingly. He also concluded that white colored delta trap was found to capture maximum mean number of *T. absoluta* moth (22) while green, yellow and orange trap was able to capture 16, 13 and 10 *T. absoluta* respectively. A maximum of 4–5 traps per ha is sufficient for monitoring whereas 10–20 traps per ha for monitoring cum mass trapping. Two more traps can be added on all four sides to deduce the direction of insect entry [42]. Water trap is also an easy control method that attracts the insect into the pan containing water and lure [63]. The vents in the roof and sides of the greenhouse or net house need to be properly screened and sealed. Double entry doors should be used carefully to prevent pests from entering the greenhouse.

Table 3
Natural enemies of *T. absoluta.*

Natural enemies	Category	Stage of insect	References
Trichogramma pretiosum (Riley)	Parasitoids	Egg	[70]
Macrolophus pygmaeus Rambu	Predator	Eggs and all larval instars	[73]
Nesidiocoris tenuis Reuter	Predator	Eggs	[74]
Pseudapanteles dignus and *Dineulophus phthorimaeae*	Parasitoids	Larva	[75]
Trichogramma exiguum Pinto & Platner	Parasitoids	Egg	[76]
Spilochalcis sps	Parasite	Pupal	[76]
Macrolophus basicornis (Stal), *Engytatus varians* (Distant) *and Campyloneuropsis infumatus* (Carvalho)	Predators	Egg	[77]

7.3. Bio-control agents

Bio-control agents should be prioritized into the management techniques to avoid excessive use of chemical pesticides. The agents include parasites, parasitoids, and natural enemies of the pest. Bio-control agents are preferred over chemical control methods as chemicals have low effect over *T. absoluta* due to the leaf-mining nature of the insect [65]. Studies on the interactions between the bio-control agents and the pest are required to explore suitable environment friendly solution against *T. absoluta* [66].

7.3.1. Predators and parasitoids

Different predators and parasitoids are used as biological control agents to reduce the population of *T. absoluta* below the economic threshold levels. Conservation and augmentative biological control programs have been developed after its invasion. Table 3 shows the natural enemies of *T. absoluta* along with the stages it feeds upon it. Hemipteran predators, notably anthocorids, geocorids, mirids, nabids, and pentatomids, have been identified as *T. absoluta* bio-control agents in both native and invaded areas. Natural predators of *T. absoluta* are *Macrolophus pygmaeus* Rambur and *Nesidiocoris tenuis* Reuter [67]. Other effective natural enemies are *Chrysoperla carnea* (Stephens) and *Dicyphus errans* (Wolff), that could be successfully integrated in pest management strategy if their habitat conservation is followed [68,69]. *Trichogramma pretiosum* (Riley) and *T. brassicae* Bezdenko are popular egg parasitoids of TLM [70]. They report that the egg parasitoid *T. pretiosum* when applied together with predatory bug *Nesidiocoris tenuis* Reuter in a TLM field affects the performance of the predator. Similarly, the effective natural enemies for parasitizing the *T. absoluta*'s larvae include *Dineulophus phthorimaeae* (de Santis) and *Pseudapanteles dingus* (Muesebeck) [71]. In particular, *P. dignus* is effective inside the greenhouse condition [72]. Some other common predators include ants, mites, spiders, and thrips, but their biological role in controlling *T. absoluta* haven't been studied yet [7]. Simultaneous application of both the predator and parasitoid affects the predation since the palatability of the pest decreases due to the presence of the parasitoid inside the prey.

Entomopathogenic microbes: *Phthorimaea operculella* granulovirus (PhopGV) has also proven effective against *T. absoluta*. Better results can be achieved if *B. thuringiensis* Berliner (Bt) is applied along with conserving the Miridae predators that feed on *Tuta* eggs [63]. However, Bt is not recommended for use in combination with chemical pesticides [78]. *B. thuringiensis* var *kursataki* is effective against the larva of *T. absoluta* under open as well as greenhouse conditions [79]. Carrera et al. [31] reported the successful larval parasitism of nematodes namely *Steinernema carpocapsae* (Weiser)*, Steinernema feltiae Filipjev,* and *Heterorhabditis* sp. for *T. absoluta*. These Entomopathogenic Nematodes (EPNs) can be either applied in soil to kill the pupating larva or in the leaves to kill the mining larvae. *Metarhizium anisopliae* (Metsch.) is effective against tomato leaf miner's pupa [80]. Inanli et al. [81] reported that both *Beauveria bassiana* (Bals.) and *M. anisopliae* (Metsch.) can be used to control *T. absoluta* (Table 4).

7.3.2. Botanical pesticides

Chinaberry (*Melia azedarach* L.*)*, Geranium (*Geranium nepalense*), Onion (*Allium cepa* L.*),* and garlic (*Allium sativum* L.) prove effective against TLM. An extract from Jojoba seeds *Simmondsia chinensis* (Link) C. K. Schneid is also effective against the second instar larva of *T. absoluta* (Table 5) [46]. Table 5 shows the plants having pesticidal property and the stage of life cycle of insect in which it is proved to be lethal. The effectiveness of the botanicals decreases in the sequence of Chinaberry, Geranium, Onion, and Garlic respectively. Azadirachtin, also a botanical, is an alkaloid obtained from Neem tree (*Azadirachta indica* A. Juss) having an anti-feedant, repellent, and sterility induction effect over the instars of *T. absoluta*. It interferes with vital life processes of the pest like ovi-position, molting, and feeding resulting in growth disorders of the insect. Application of azadirachtin is relatively more effective in the early two instars of the larva than during the later stages [87].

8. Insecticide resistance and side effects on biological control

Insecticide resistance against *T. absoluta* has been detected from various parts of the world [93]. Resistance to pyrethroids, cartap, and organophosphates was observed in South America [94]. Widespread pyrethroid resistance and moderate indoxacarb, spinosyn, and spinosad resistance were detected in Europe [95]. In Brazil and Europe, resistance to diamide is rising and altered target site sensitivity to chlorantraniliprole and spinosad has been recently reported [13]. Insecticide resistance can lead to failure in the control of pest population and it is crucial to pay attention to this problem. The use of Geographic information system (GIS) and spatial surveys can be used to identify the areas of high risk to resistance. Such efforts allow recognition of concerning regions at risk for further intervention [96].

Insecticides have pernicious effects on beneficial arthropods either directly by acute toxicity or by sub-lethal effects [97]. The excessive use of chemical insecticide can cause disruption of IPM programs. According to Martinou et al. [98], Chlorantraniliprole

Table 4
Microbial agents used against *T. absoluta*.

Microbial agent	Stage of insect	References
Metarhizium anisopliae (Metsch.)	Larva and Pupa	[82]
Bacillus thuringiensis Berliner	Second instar larvae	[83]
Beauveria bassiana (Bals.)	Just hatched to the 4th instar	[84]
Bacillus thuringiensis var. *kurstaki*	Newly hatched, 2nd and 3rd instar larvae	[85]
Beauveria bassiana Bals.-Criv. *Metarhizium anisopliae* (Metchnikoff) Sorokīn	3rd Instar larvae	[86]

Table 5
Botanical insecticides used against *T. absoluta*.

Common name	Botanical name	Stage of insect	References
Neem	*Azadirachta indica* A. Juss	Egg and Larva	[88]
Jatropa	*Jatropa curcas* L.	Larva	[88,89]
Jojoba seeds	*Simmondsia chinensis.*	2nd Instar larva	[46]
Garlic	*Allium sativum* L.	2nd Instar larva	[90]
Chinaberry	*Melia azedarach* L.	2nd Instar larva	[90]
Onion	*Allium cepa* L.	2nd Instar larva	[90]
Pepper	*Piper amalago* var. *medium*	Larva and pupa	[91]
Toothache Plant	*Acmella oleracea* (L.) R.K. Jansen	All	[89]
Southern Blue Gum	*Eucalyptus globulus* Labill.	Larva	[92]

residues lead to a reduction of bio-control activity of *B. nigricans* when the temperature is 35° C [99]. However, laboratory studies show that chlorantraniliprole has no effects on the survival and reproduction of generalist predators [100]. The insecticides that are registered for organic production may also threaten the effectiveness of natural enemies of *T. absoluta*. The recommended dose of spinosad in Brazil caused high mortality in predatory wasps, and the impact lasted for quite a month in absence of rainfall [101]. Exposure to residues is found to reduce the fecundity of flower bugs and the mobility of stink bugs and earwigs [13]. However, the lower negative effects have been reported from the use of botanical insecticide Azadirachtin [100].

9. Use of chemical pesticides for management of *T. absoluta*

Chemical insecticides like Spinosad, Emamectin benzoate, Triflumuron, and Diafenthiuron are effective against *T. absoluta*. Spinosad, Chlorantraniliprole, and Novaluron are among the chemicals that are advised in Nepal for the control of this pest, but studies have shown that these chemicals are ineffective due to the pest's wide host range, rapid reproductive ability, and development of pesticide resistance [102]. Synthetic chemical pesticides that are used in management of *T. absoluta* is given in Table 6. Bastola et al. [20] concluded from his research conducted in Palpa, Nepal that spinosad, followed by chlorantraniliprole, emamectin benzoate, and spinosad, had the lowest proportion of leaves damaged, whereas chlorantraniliprole had the lowest percentage of fruit damage. Also, spinosad, emamectin benzoate, and chlorantraniliprole were shown to have the lowest larvae populations in both leaves and fruits. Likewise, Simkhada et al. [103] found that chlorantraniliprole was the most efficacious and resulted in lower number of mines per leaf in the research conducted at Kavresthali, Kathmandu. An increased efficacy can be observed when these chemicals are used along with plant extracts [104]. Continuous use of such chemicals may cause the development of insect resistance against insecticide [105]. This is a serious problem in the present context because stable production of agricultural crops is impossible without pest control. Study suggested a failure of Indoxacarb at controlling *T. absoluta* as higher instances of resistance development were observed with insect group treated under it as compared to chlorantraniliprole, emamectin benzoate, and spinosad [106]. Hence, a single chemical shall not be relied upon for controlling the pest, either the chemicals should be changed on a regular basis or alternative methods must be used.

10. Tomato resistance and breeding programs

Cultivated tomatoes are highly vulnerable to *T. absoluta*, and most promising genetic sources of resistance are wild tomatoes [108]. Tomato resistance to *T. absoluta* has been the focus of attention in breeding programs relying on resistance related to allelochemicals and trichome density. Trichomes containing 2-tridecanone, zingiberene and acyl sugars, possess high deterrent activity on *T. absoluta.* These compounds impair egg laying and larval feeding, leading to antixenosis and larval toxicity leading to antibiosis. Chewing of plants by *T. absoluta* triggers the volatile organic compounds that enhances plant defense against various pests and attracts natural enemies [7]. However, manipulating resistance to *T. absoluta* may perturb micro and macro organism communities of tomato that may lead to various unanticipated consequences to yield.

11. Sex pheromone and hormonal based control measures

Hormones are chemicals with multitude functions, of which one is it influence the behavior of the opposite sex, such as triggering sexual interest and excitement. Hormones do not leave any persistent residue and donot have any hazardous effect on human health. Pheromones are recommended to be used in combination with other techniques, as it is an environmentally safe management method.

Table 6
Synthetic chemical insecticides used against *T. absoluta.*

Technical name	Dose	Remarks	Waiting period	Hazardous level	Source
Chlorantraniliprole 18.5% SC	1 ml per 3 ml water	Spray in interval of 10–15 days	7 days	Unlikely to present acute hazard	[107]
Spinosad 45% SC	1 ml per 3 L water	Spray in interval of 10–15 days	7 days	Slightly hazardous	[107]
Emamectin benzoate 5%WG	5 gm per 16 L water	Spray in interval of 10–15 days	10 days	Moderately hazardous	[4]
Flubendiamide 39.35% SC	1 ml/3–5 L water	Spray in interval of 10–15 days	7 days	Moderately hazardous	[4]

Recently introduced, insect hormones seem to have no residual side effects. It has been successfully applied in controlling leaf miners in both greenhouses and open fields in many places like South America, Europe, Asia, and North Africa. The same can be adapted in Nepal too. Pheromone acts as a natural sexual attractant. Chemical signals released by an organism to attract an individual of the same species of the opposite sex are known as sex pheromones. *T. absoluta* pheromone lure has been identified as 3,8,11-tetradecatrienyl acetate as major and tetradecadien-1-yl acetate minor component [109]. The use of pheromone is more recommended to be used in combination with other techniques, as it is an environmentally safe management method. Pyriproxyfen, a juvenile hormone mimic, causing mortality of half the population of early larva underexposure, has been successfully applied in controlling leaf miners on both greenhouses and open fields in many places like South America, Europe, Asia, and North Africa [110]. In Egypt, a study conducted by El-Aassar [111], where sex-pheromone was combined with other pesticides in controlling leafminer infestation on tomatoes showed a promising result.

11.1. Interaction between multiple pest control factors

Before applying different pest control methods, the compatibility between the control measures needs to be checked carefully. For instance, simultaneous use of the chemical insecticide and Bt is not recommended for *T. absoluta* control as an appropriate time interval should be taken into consideration accordingly [78]. According to a study conducted by Amizadeh [78], when Bt was applied immediately after the application of chemical insecticides and Azadiractin an antagonistic effect was observed. Azadirachtin initially may have decreased larval feeding and as a result, less amount of Bt was consumed by the larvae. Single management practice is not enough for the control of *Tuta*. Therefore, different control measures i.e., biological, mechanical, and chemical methods must be applied to observe its combined effect.

The study conducted by Faria et al. [112] reported that plant structure was not associated with the efficiency of *T. pretiosum* (Riley), however, pest-infested plant apexes had a healthy pest population and were highest in the upper portion of the plant stem; the pest infestation decreased with plant height from the ground level. It is smart not to be using *T. pretiosum* in combination with such antagonistic insecticides. The use of insecticides like cartap, phenthoate, lambda-cyhalothrin, emamectin benzoate, tebufenozide, and teflubenzuron to control *T. absoluta* affects the natural enemy *T. pretiosum* with slight to large negative effects [113].

The farmers apply highly toxic insecticides to their fields for immediate knockdown effects without knowing the consequences. This brings further pest problems. Preventing such consequences requires sustainable measures that are not as potent in the short term but show much better results in the long term. Eco-friendly and effective, IPM practices are the best-known pest control methods in the present times. Different IPM practices are followed to control *T. absoluta* in Nepal. Chemical pesticides were found to be successful initially. However, research on the negative effects of synthetic chemicals on the environment made the scientific community look for sustainable and eco-friendly alternatives. The use of natural enemies, hormones, botanical pesticides, and physio-mechanical traps are among the most effective alternatives in the current scenario. Scientists working in this field are carrying studies to evaluate and determine the optimum pest management.

Hormonal action to monitor the population level of *T. absoluta* combined with biological management approaches could be adopted in Nepal for the eco-friendly management of tomato leaf miners. One major problem is the reluctance of farmers to accept such measures. This can only be solved if the government can build model farms using IPM practices all over the country. It is the only way to make the farmers put faith in these modern control measures.

12. Conclusion

T. absoluta is a noxious invasive pest for global and Nepalese agriculture. It can infest and damage wide areas of cultivated fields of tomato production as well as other solanaceous crop plants, for example, potatoes, eggplant, and chili peppers. Several studies revealed that this pest can infest both protected as well as open fields, and can spread rapidly resulting in a significant reduction in the yield and quality of the crop. This devastating pest is likely to disseminate rapidly and has the potential to cause huge damage. But controlling this damage demands an effective way apart from the use of toxic compounds. An ecofriendly and efficient pest control measure like IPM is the rational way of tackling the problems due to infestation of *T. absoluta*. The government needs to change the modality of extension. Government and concerned authority should go for biological control of *T. absoluta* in combination with other packages for sustainable way for the management of *T. absoluta.*

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

No data was used for the research described in the article.

Declaration of competing interest

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

References

[1] N.F. Abdel-Baky, S.S. Alhewairini, M.M. Al-Azzazy, M.Z. Qureshi, M.A. Al-Deghairi, J. Hajjar, Efficacy of *Metarhizium anisopliae* and *Beauveria bassiana* against *Tuta absoluta* (Lepidoptera: Gelechiidae) eggs under laboratory conditions, Pakistan J. Agric. Sci. 58 (2021) 743–750, https://doi.org/10.21162/PAKJAS/21.52.

[2] S.Ş. Hogea, *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae) – biology, ecology, prevention and control measures and means in greenhouse tomato crops. A review, Current Trends in Natural Sciences 9 (2020) 222–231, https://doi.org/10.47068/ctns.2020.v9i17.028.

[3] H.E.Z. Tonnang, S.F. Mohamed, F. Khamis, S. Ekesi, Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: implications for phytosanitary measures and management, PLoS One 10 (2015) 1–19, https://doi.org/10.1371/journal.pone.0135283.

[4] I. Rwomushana, T. Beale, R. Chipabika, Day Gilson, P. Gonzalez-Moreno, Evidence Note Tomato Leafminer Impacts and Coping Strategies for Africa Authors, 2019.

[5] Ç. Gözel, İ. Kasap, U. Gözel, Efficacy of native entomopathogenic nematodes on the larvae of tomato leafminer *Tuta absoluta* (Meyrick) (lepidoptera: Gelechiidae), J. Agric. Sci. 26 (2020) 220–225, https://doi.org/10.15832/ankutbd.519686.

[6] N. Desneux, E. Wajnberg, K.A.G. Wyckhuys, G. Burgio, S. Arpaia, C.A. Narváez-Vasquez, J. González-Cabrera, D.C. Ruescas, E. Tabone, J. Frandon, J. Pizzol, C. Poncet, T. Cabello, A. Urbaneja, Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control, J. Pest. Sci. 83 (2010) 197–215, https://doi.org/10.1007/s10340-010-0321-6.

[7] A. Biondi, R.N.C. Guedes, F.H. Wan, N. Desneux, Ecology, worldwide spread, and management of the invasive South American tomato pinworm, *Tuta absoluta*: past, present, and future, Annu. Rev. Entomol. 63 (2018) 239–258, https://doi.org/10.1146/annurev-ento-031616-034933.

[8] G.T. Garzia, G. Siscaro, A. Biondi, L. Zappalà, *Tuta absoluta,* a South American pest of tomato now in the EPPO region: biology, distribution and damage, EPPO/EPPO. 42 (2012) 205–210, https://doi.org/10.1111/epp.2556.

[9] S. Moussa, A. Sharma, F. Baiomy, F.E. El-Adl, The status of tomato leafminer; *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Egypt and potential effective pesticides, Acad. J. Entomol. 6 (2013) 110–115, https://doi.org/10.5829/idosi.aje.2013.6.3.75130.

[10] D. Son, S. Bonzi, I. Somda, T. Bawin, S. Boukraa, F. Verheggen, F. Francis, A. Legreve, B. Schiffers, First record of *Tuta absoluta* (meyrick, 1917) (Lepidoptera: Gelechiidae) in Burkina Faso, Afr. Entomol. 25 (2017) 259–263, https://doi.org/10.4001/003.025.0259.

[11] A.S. Bajracharya, R.P. Mainali, B. Bhat, S. Bista, P.R. Shashank, N.M. Meshram, The first record of South American tomato leaf miner, *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Nepal, Journal of Entomology and Zoology Studies 4 (2016) 1359–1363.

[12] S.R. Benvenga, O.A. Fernandes, S. Gravena, Tomada de decisão de controle da traça-do-tomateiro através de armadilhas com feromônio sexual, Hortic. Bras. 25 (2007) 164–169, https://doi.org/10.1590/s0102-05362007000200007.

[13] M.R. Campos, A.R.S. Rodrigues, W.M. Silva, T.B.M. Silva, V.R.F. Silva, R.N.C. Guedes, H.A.A. Siqueira, Spinosad and the tomato borer *Tuta absoluta*: a bioinsecticide, an invasive pest threat, and high insecticide resistance, PLoS One 9 (2014) 1–12, https://doi.org/10.1371/journal.pone.0103235.

[14] E. Roditakis, E. Vasakis, L. García-Vidal, M. del R. Martínez-Aguirre, J.L. Rison, M.O. Haxaire-Lutun, R. Nauen, A. Tsagkarakou, P. Bielza, A four-year survey on insecticide resistance and likelihood of chemical control failure for tomato leaf miner *Tuta absoluta* in the European/Asian region, J. Pest. Sci. 91 (2018) 421–435, https://doi.org/10.1007/s10340-017-0900-x.

[15] M.A. Soares, M.R. Campos, *Phthorimaea Absoluta* (Tomato Leafminer), CABI, 2020. https://www.cabi.org/isc/datasheet/49260.

[16] A. Urbaneja, R. Vercher, V. Navarro, y F.G. Mari, J.L. Porcuna, La polilla del tomate, *Tuta absoluta*, Phytoma Espa (2007) 16–23.

[17] O. Karadjova, Z. Ilieva, V. Krumov, E. Petrova, V. Ventsislavov, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae): potential for entry, establishment and spread in Bulgaria, Bulgarian Journal of Agricultural Science 19 (2013) 563–571.

[18] N. Zekeya, M. Chacha, P. Ndakidemi, C. Materu, M. Chidege, E. Mbega, Tomato leafminer (*Tuta absoluta* Meyrick 1917): a threat to tomato production in Africa, Journal of Agriculture and Ecology Research International 10 (2017) 1–10, https://doi.org/10.9734/jaeri/2017/28886.

[19] A. Harbi, K. Abbes, B. Chermiti, Evaluation of two methods for the protection of tomato crops against the tomato leafminer *Tuta absoluta* (Meyrick) under greenhouses in Tunisia, OEPP/EPPO. 42 (2012) 317–321, https://doi.org/10.1111/epp.2576.

[20] A. Bastola, S.R. Pandey, A. Khadka, R. Regmi, Efficacy of commercial insecticides against tomato leaf miner *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae) in Palpa, Nepal, Turkish Journal of Agriculture - Food Science and Technology 8 (2020) 2388–2396, https://doi.org/10.24925/turjaf.v8i11.2388-2396.3680.

[21] R. Mansour, T. Brévault, A. Chailleux, A. Cherif, K. Grissa-Lebdi, K. Haddi, S.A. Mohamed, R.S. Nofemela, A. Oke, S. Sylla, H.E.Z. Tonnang, L. Zappalà, M. Kenis, N. Desneux, A. Biondi, Occurrence, biology, natural enemies and management of *Tuta absoluta* in Africa, Entomol. Gen. 38 (2018) 83–112, https://doi.org/10.1127/entomologia/2018/0749.

[22] R.A. Guimapi, R. Srinivasan, H.E. Tonnang, P. Sotelo-Cardona, S.A. Mohamed, Exploring the mechanisms of the spatiotemporal invasion of *Tuta absoluta* in Asia, Agriculture (Switzerland) 10 (2020) 1–12, https://doi.org/10.3390/agriculture10040124.

[23] E. Sankarganesh, D.M. Firake, B. Sharma, V.K. Verma, G.T. Behere, Invasion of the South American Tomato Pinworm, *Tuta absoluta*, in northeastern India: a new challenge and biosecurity concerns, Entomol. Gen. 36 (2017) 335–345, https://doi.org/10.1127/entomologia/2017/0489.

[24] M.R. Campos, A. Biondi, A. Adiga, R.N.C. Guedes, N. Desneux, From the western palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe, J. Pest. Sci. 90 (2017) 787–796, https://doi.org/10.1007/s10340-017-0867-7.

[25] IPM Innovation Lab, *Tuta Absoluta*: the South American Tomato Leafminer, Feed for Future, 2014. https://ipmil.cired.vt.edu/tuta-absoluta/.

[26] EPPO Global Database, *Tuta absoluta* (GNORAB), 2022. https://gd.eppo.int/taxon/GNORAB/distribution.

[27] L.P. Sah, M. Devkota, L.A. Colavito, Y. Dhakal, S. Yendyo, D.R. Sharma, G. Norton, E.G. Rajotte, S. Paudel, R. Muniappan, Tomato leafminer , *Tuta absoluta* and its management in Nepal, in: Integrated Pest Management of Tropical Crops, 2017. https://www.researchgate.net/publication/326318456_Tomato_Leafminer_Tuta_absoluta_Meyrick_and_its_management_in_Nepal.

[28] D. Joshi, B.P. Rajbhnadari, B.P. Bhattarai, L. Sah, Local innovation documentation: a case study of Mustang district, Nepal, Nepalese Journal of Agricultural Sciences 15 (2017) 93–97.

[29] A.S.R. Bajracharya, B. Bhat, P.N. Sharma, Geographical distribution of south AMERICAN tomato leaf miner *Tuta absoluta* (meyrick, 1917) (lepidoptera: GELECHIIDAE) in Nepal. Ajaya, Journal of Plant Protection Society 5 (2018) 203–216.

[30] J.B. Torres, C.A. Faria, W.S.J. Evangelista, D. Pratissoli, Within-plant distribution of the leaf miner *Tuta absoluta* (Meyrick) immatures in processing tomatoes, with notes on plant phenology, Int. J. Pest Manag. 47 (2001) 173–178, https://doi.org/10.1080/02670870010011091.

[31] L.B. Carrera, A. Morton, F. García-del-Pino, Efficacy of entomopathogenic nematodes against the tomato leafminer *Tuta absoluta* in laboratory and greenhouse conditions, BioControl 55 (2010) 523–530, https://doi.org/10.1007/s10526-010-9284-z.

[32] R.J. Sinclair, L. Hughes, Leaf miners: the hidden herbivores, A Journal of Ecology in the Southern Hemisphere 35 (2010) 300–313.

[33] K. Godfrey, F. Zalom, J. Chiu, Tuta Absoluta the South American Tomato Leafminer, Californi, 2018, https://doi.org/10.3733/ucanr.8589.

[34] S.D.L. Imenes, M.A.U. Fernandes, T.B. de Campos, A.P. Takematsu, Aspects of the Biology and Behaviour of the Tomato Moth Scrobipalpula Absoluta (Meyrick, 1917) (Lepidoptera: Gelechiidae), Arquivos Do Instituto Biológico (São Paulo), 1990, pp. 63–68. https://www.cabdirect.org/cabdirect/abstract/19951107883.

[35] IRAC, Tuta absoluta, The Tomato Leafminer or Tomato Borer, 2014.

[36] N. Victor, M. Mwangi, Prevalence of *Tuta absoluta* (meyrick) and chemical management in loitoktok , kajiado county , Kenya, Journal of Biology, Agriculture and Healthcare 9 (2019) 27–37.

[37] B. Aynalem, Tomato leafminer [(*Tuta absoluta* Meyrick) (Lepidoptera: Gelechiidae)] and its current ecofriendly management strategies : a review, J. Agric. Biotechnol. Sustain. Dev. 10 (2018) 11–24, https://doi.org/10.5897/JABSD2018.0306.

[38] P. Pascal, Tomato Farming: Biology and Origin of *Tuta absoluta*, Zambia Agribusiness Society, 2020.

[39] A. Cherif, F. Verheggen, A review of *Tuta absoluta* (Lepidoptera : Gelechiidae) host plants and their impact on management strategies, Biotechnol. Agron. Soc. Environ. 23 (2019) 270–278.

[40] E.S.I. Mohamed, M.E.E. Mahmoud, M.A.M. Elhaj, S.A. Mohamed, S. Ekesi, Host plants record for tomato leaf miner *Tuta absoluta* (Meyrick) in Sudan, OEPP/EPPO. 45 (2015) 108–111, https://doi.org/10.1111/epp.12178.
[41] J.D. Smith, T. Dubois, R. Mallogo, E.F. Njau, S. Tua, R. Srinivasan, Host range of the invasive tomato pest *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) on solanaceous crops and weeds in Tanzania, Fla. Entomol. 101 (2018) 573–579, https://doi.org/10.1653/024.101.0417.
[42] R. Megido, E. Haubruge, F.J. Verheggen, Pheromone-based management strategies to control the tomato leafminer, Tuta absoluta (Lepidoptera: Gelechiidae). A review | Synthèse bibliographique: Les stratégies de lutte phéromonale utilisées pour contrôler la mineuse de la tomate, Tuta absoluta (Lepi, Biotechnology, 17, Agronomy and Society and Environment, 2013, pp. 475–482.
[43] G. Gebremariam, *Tuta absoluta* : a global looming challenge in tomato production , review paper, Journal of Biology, Agriculture and Healthcare 5 (2015) 57–63.
[44] G.E.A. Idriss, H. Du Plessis, F.M. Khamis, S. Ekesi, C.M. Tanga, S.A. Mohamed, Host range and effects of plant species on preference and fitness of *Tuta absoluta* (Lepidoptera: Gelechiidae), J. Econ. Entomol. 113 (2020) 1279–1289, https://doi.org/10.1093/jee/toaa002.
[45] M.N. Huda, T. Jahan, H.F. El Taj, K.A. Asiry, A newly emerged pest of tomato [tomato leaf miner, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae)]: in Bangladesh – a review on its problems and management strategies, Journal of Agriculture and Ecology Research International 21 (2020) 1–16, https://doi.org/10.9734/jaeri/2020/v21i330132.
[46] N.F. Abdel-Baky, A.A. Al-Soqeer, Controlling the 2nd instar larvae of *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) by simmondsin extracted from jojoba seeds in KSA, J. Entomol. 14 (2017) 73–80.
[47] A.M. Simmons, W. Wakil, M.A. Qayyum, S. Ramasamy, T.P. Kuhar, C.R. Philips, Lepidopterous Pests: Biology, Ecology, and Management, Elsevier Inc., 2017, https://doi.org/10.1016/B978-0-12-802441-6.00006-1.
[48] A.N. Retta, D.H. Berhe, Tomato leaf miner – *Tuta absoluta* (Meyrick), a devastating pest of tomatoes in the highlands of Northern Ethiopia : a call for attention and action, Research Journal of Agriculture and Environmental Manage 4 (2015) 264–269.
[49] EPPO Global Database, *Tuta Absoluta* (GNORAB), 2022. https://gd.eppo.int/taxon/GNORAB/hosts.
[50] J. Arnó, R. Gabarra, P. Molina, K.E. Godfrey, F.G. Zalom, *Tuta absoluta* (Lepidoptera: Gelechiidae) success on common solanaceous species from California tomato production areas, Environ. Entomol. 48 (2019) 1394–1400, https://doi.org/10.1093/ee/nvz109.
[51] P.C. Gontijo, M.C. Picanço, E.J.G. Pereira, J.C. Martins, M. Chediak, R.N.C. Guedes, Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta*, Ann. Appl. Biol. 162 (2013) 50–59, https://doi.org/10.1111/aab.12000.
[52] P.R. Shashank, K. Chandrashekar, N.M. Meshram, K. Sreedevi, Occurrence of *Tuta absoluta* (Lepidoptera: Gelechiidae) an invasive pest from India, Indian Journal of Agricultural Entomology 77 (2015) 323–329.
[53] T. Shiberu, E. Getu, Experimental analysis of ecomomic action level of tomato leafminer, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) on tomato plant under open field, Advances in Crop Science and Technology 6 (2018) 1–5, https://doi.org/10.4172/2329-8863.1000327.
[54] B. Chermiti, K. Abbes, M. Aoun, S. Ben, M. Ouhibi, W. Gamoon, S. Kacem, First estimate of the damage of *Tuta absoluta* (povolny) (Lepidoptera: Gelechiidae) and evaluation of the efficiency of sex pheromone traps in greenhouses of tomato crops in the bekalta region , Tunisia, Afr. J. Plant Sci. Biotechnol. 3 (2009) 49–52.
[55] E.S.I. Mohamed, M.E. Mohamed, S.A. Gamiel, First record of the tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Sudan, OEPP/EPPO. 42 (2012) 325–327, https://doi.org/10.1111/epp.2578.
[56] M. Chidege, J. Abel, Z. Afonso, M. Tonini, B. Fernandez, Tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) detected in namibe province Angola, Journal of Applied Life Sciences International 12 (2017) 1–5, https://doi.org/10.9734/jalsi/2017/33725.
[57] M.S.A. Luangala, K.K. Msiska, M.D. Chomba, M. Mudenda, P.S. Mukuwa, First Report of *Tuta Absoluta* (Meyrick) Zambia, 2016.
[58] M. Chidege, S. Al-zaidi, N. Hassan, A. Julie, E. Kaaya, S. Mrogoro, First record of tomato leaf miner *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) in Tanzania, Agric. Food Secur. 5 (2016) 1–7, https://doi.org/10.1186/s40066-016-0066-4.
[59] M.L. Flint, IPM in Practice, second ed., University of California Agriculture and Natural Resources., California, 2012.
[60] A. Joshi, R.B. Thapa, D. Kalauni, Integrated management of south AMERICAN tomato leaf miner [Tuta absoluta (meyrick)]: a review, Journal of the Plant Protection Society 5 (2018) 70–86.
[61] L.B. Chhetri, Tomato Leafminer (*Tuta absoluta*) an emerging agricultural pest : control and management strategies : a Review, World Scientific News 114 (2018) 30–43.
[62] D.T. Illakwahhi, P.B.B.L. Srivastava, Control and management of tomato leafminer -*Tuta absoluta* (meyrick) (lepidotera, Gelechiidae).A review, IOSR J. Appl. Chem. 10 (2017) 14–22, https://doi.org/10.9790/5736-1006011422.
[63] J.C. González, O. Mollá, H. Montón, A. Urbaneja, Efficacy of Bacillus thuringiensis (Berliner) in controlling the tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), BioControl 56 (2011) 71–80, https://doi.org/10.1007/s10526-010-9310-1.
[64] J. Kadel, L.P. Sah, M. Devkota, L.A. Colavito, G. Norton, E.G. Rajotte, R. Muniappan, Effectiveness of different types of traps for management of *Tuta absoluta* in Nepal, Journal of Plant Protection Society 5 (2018) 166–174.
[65] L. Schäfer, A. Herz, Suitability of european trichogramma species as biocontrol agents against the tomato leaf miner *Tuta absoluta*, Insects 11 (2020) 1–18, https://doi.org/10.3390/insects11060357.
[66] P. Cascone, S. Carpenito, S. Slotsbo, L. Iodice, J.G. Sørensen, M. Holmstrup, E. Guerrieri, Improving the efficiency of *Trichogramma achaeae* to control *Tuta absoluta*, BioControl 60 (2015) 761–771, https://doi.org/10.1007/s10526-015-9684-1.
[67] J. Arnó, R. Gabarra, Side effects of selected insecticides on the *Tuta absoluta* (Lepidoptera: Gelechiidae) predators *Macrolophus pygmaeus* and *Nesidiocoris tenuis* (Hemiptera: Miridae), J. Pest. Sci. 84 (2011) 513–520, https://doi.org/10.1007/s10340-011-0384-z.
[68] B.L. Ingegno, C. Ferracini, D. Gallinotti, A. Alma, L. Tavella, Evaluation of the effectiveness of Dicyphus errans (wolff) as predator of *Tuta absoluta* (Meyrick), Biol. Control 67 (2013) 246–252, https://doi.org/10.1016/j.biocontrol.2013.08.002.
[69] K. Ismoilov, M. Wang, A. Jalilov, X. Zhang, Z. Lu, A. Saidov, X. Sun, P. Han, First report using a native lacewing species to control *Tuta absoluta*: from laboratory trials to field assessment, Insects 11 (2020) 1–12, https://doi.org/10.3390/insects11050286.
[70] M.A. Mirhosseini, Y. Fathipour, N. Holst, M. Soufbaf, J.P. Michaud, An egg parasitoid interferes with biological control of tomato leafminer by augmentation of *Nesidiocoris tenuis* (Hemiptera: Miridae), Biol. Control 133 (2019) 34–40, https://doi.org/10.1016/j.biocontrol.2019.02.009.
[71] M.G. Luna, P.C. Pereyra, C.E. Coviella, E. Nieves, V. Savino, N.G.S. Gervassio, E. Luft, E. Virla, N.E. Sánchez, Potential of Biological Control Agents against *Tuta absoluta* (Lepidoptera: Gelechiidae): Current Knowledge in Argentina, Florida Entomologist, 2015, https://doi.org/10.1653/024.098.0215.
[72] M.G. Luna, N.E. Sánchez, P.C. Pereyra, Parasitism of *Tuta absoluta* (Lepidoptera, Gelechiidae) by *Pseudapanteles dignus* (hymenoptera, braconidae) under laboratory conditions, Environ. Entomol. 36 (2007) 887–893.
[73] Ó. Mollá, H. Montón, P. Vanaclocha, F. Beitia, A. Urbaneja, Predation by the mirids *Nesidiocoris tenuis* and *Macrolophus pygmaeus* on the tomato borer *Tuta absoluta*, in: Proceedings of the IOBC/WPRS Working Group "Integrated Control in Protected Crops", 2009, pp. 209–214. Crete, Greece, 6-11 September 2009, https://www.cabdirect.org/cabdirect/abstract/20113278097. Crete, Greece, 6-11 September 2009.
[74] O. Mollá, J. González-Cabrera, A. Urbaneja, The combined use of *Bacillus thuringiensis* and *Nesidiocoris tenuis* against the tomato borer *Tuta absoluta*, BioControl 56 (2011) 883–891, https://doi.org/10.1007/s10526-011-9353-y.
[75] N.E. Sánchez, P.C. Pereyra, M.G. Luna, Spatial patterns of parasitism of the solitary parasitoid pseudapanteles dignus (Hymenoptera: braconidae) on *Tuta absolute* (Lepidoptera: Gelechiidae), Environ. Entomol. 38 (2009) 365–374, https://doi.org/10.1603/022.038.0208.
[76] G.R. Vasconcelos, Strain Selection and Host Effect on Trichogramma Pretiosum Riley 1879 (Hymenoptera: Trichogrammatidae) Quality for *Tuta absoluta* (Meyrick, 1917)(Lepidoptera: Gelechiidae) Control in Tomato Crops, Univ. Moura Lacerda, Brasil, 2013.
[77] J.C. van Lenteren, L. Hemerik, J.C. Lins, V.H.P. Bueno, Functional Responses of three neotropical mirid predators to eggs of *Tuta absoluta* on tomato, Insects 7 (2016) 1–10, https://doi.org/10.3390/insects7030034.
[78] M. Amizadeh, M.J. Hejazi, G. Niknam, M. Arzanlou, Compatibility and interaction between Bacillus thuringiensis and certain insecticides: perspective in management of *Tuta absoluta* (Lepidoptera: Gelechiidae), Biocontrol Sci. Technol. 25 (2015) 671–684, https://doi.org/10.1080/09583157.2015.1007030.

[79] M.M. Sabbour, N. Soliman, Evaluations of three Bacillus thuringiensis against *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae) in Egypt, Int. J. Sci. Res. 3 (2014) 2067–2073, https://doi.org/10.13140/RG.2.1.3355.3765.
[80] J. Contreras, J.E. Mendoza, M.R. Martínez-Aguirre, L. García-Vidal, J. Izquierdo, P. Bielza, Efficacy of enthomopathogenic fungus Metarhizium anisopliae against *Tuta absoluta* (Lepidoptera: Gelechiidae), J. Econ. Entomol. 107 (2014) 121–124, https://doi.org/10.1603/EC13404.
[81] C. Inanli, Z. Yoldas, A.K. Birgucu, Effects of entomopathogenic fungi, Beauveria bassiana (Bals.) and Metarhizium anisopliae (Metsch.) on larvae and egg stages of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), Ege Univ. Ziraat Fak. Derg. 49 (2012) 239–242.
[82] A.P. Giri, L. Sah, IPM Recommendations for Management of *Tuta absoluta* Major Highlights Recommendations for Management of Tuta Absoluta for Green Houses with, Lalitpur, 2017.
[83] J. Halder, D. Kushwaha, A.B. Rai, B. Singh, Biology and biorational management of *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae): a global challenge to tomato production, Proc. Zool. Soc. 72 (2019) 107–110, https://doi.org/10.1007/s12595-017-0232-0.
[84] T.A. Giustolin, J.D. Vendramim, S.B. Alves, S.A. Vieira, Patogenicidade de Beauveria bassiana (Bals.) Vuill. sobre *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) criada em dois genótipos de tomateiro, Neotrop. Entomol. 30 (2001) 417–421, https://doi.org/10.1590/S1519-566X2001000300013.
[85] H.H. Shalaby, F.H. Faragalla, H.M. El-Saadany, A.A. Ibrahim, Efficacy of three entomopathogenic agents for control the tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), Nat. Sci. 11 (2013) 63–72.
[86] M. Sabbour, Biocontrol of the tomato pinworm *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae) in Egypt, Middle East, Journal of Agriculture Research 3 (2014) 499–503.
[87] A. Berxolli, S. Shahini, Azadirachtin, a useful alternative for controlling *Tuta absoluta* (Myerick), European Journal of Physical and Agricultural Sciences 5 (2017) 40–45. www.idpublications.org.
[88] N.E.M. Kona, A.K. Taha, M.E.E. Mahmoud, Effects of Botanical Extracts of Neem(Azadirachta indica) and Jatropha (Jatropha Curcus) on Eggs and Larvae of Tomato Leaf Miner, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae), 3, Persian Gulf Crop Protection, 2014, pp. 41–46.
[89] S.C. Moreno, G.A. Carvalho, M.C. Picanço, E.G.F. Morais, R.M. Pereira, Bioactivity of compounds from Acmella oleracea against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) and selectivity to two non-target species, Pest Manag. Sci. 68 (2011) 386–393, https://doi.org/10.1002/ps.2274.
[90] N.M. Ghanim, S.B. Ghani, Controlling *Tuta absoluta* (Lepidoptera: Gelechiidae) and *Aphis gossypii* (Hemiptera: aphididae) by aqueous plant extracts, Life Sci. J. 11 (2014) 299–307.
[91] E.F. de Brito, E.L.L. Baldin, R. de C.M. Silva, L. do P. Ribeiro, J.D. Vendramim, Bioactivity of piper extracts on *Tuta absoluta* (Lepidoptera: Gelechiidae) in tomato, Pesqui. Agropecu. Bras. 50 (2015) 196–202, https://doi.org/10.1590/S0100-204X2015000300002.
[92] N. Sanda, M. Sunusi, H. Hamisu, B. Wudil, H. Sule, A. Abdullahi, Biological invasion of tomato leaf miner, *Tuta absoluta* (meyrick) in Nigeria: problems and management strategies optimization: a review, Asian Journal of Agricultural and Horticultural Research 1 (2018) 1–14, https://doi.org/10.9734/ajahr/2018/41959.
[93] R.N.C. Guedes, M.C. Picanço, The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance, OEPP/EPPO. 42 (2012) 211–216, https://doi.org/10.1111/epp.2557.
[94] R.N.C. Guedes, E. Roditakis, M.R. Campos, K. Haddi, P. Bielza, H.A.A. Siqueira, A. Tsagkarakou, J. Vontas, R. Nauen, Insecticide resistance in the tomato pinworm *Tuta absoluta*: patterns, spread, mechanisms, management and outlook, J. Pest. Sci. 92 (2019) 1329–1342, https://doi.org/10.1007/s10340-019-01086-9.
[95] E. Roditakis, C. Skarmoutsou, M. Staurakaki, Toxicity of insecticides to populations of tomato borer *Tuta absoluta* (Meyrick) from Greece, Pest Manag. Sci. 69 (2013) 834–840, https://doi.org/10.1002/ps.3442.
[96] R.N.C. Guedes, Insecticide resistance, control failure likelihood and the First Law of Geography, Pest Manag. Sci. 73 (2017) 479–484, https://doi.org/10.1002/ps.4452.
[97] N. Desneux, A. Decourtye, J.M. Delpuech, The sublethal effects of pesticides on beneficial arthropods, Annu. Rev. Entomol. 52 (2007) 81–106, https://doi.org/10.1146/annurev.ento.52.110405.091440.
[98] A.F. Martinou, N. Seraphides, M.C. Stavrinides, Lethal and behavioral effects of pesticides on the insect predator Macrolophus pygmaeus, Chemosphere 96 (2014) 167–173, https://doi.org/10.1016/j.chemosphere.2013.10.024.
[99] K. Abbes, A. Biondi, A. Kurtulus, M. Ricupero, A. Russo, G. Siscaro, B. Chermiti, L. Zappalà, Combined non-Target effects of insecticide and high temperature on the parasitoid bracon nigricans, PLoS One 10 (2015) 1–14, https://doi.org/10.1371/journal.pone.0138411.
[100] A. Biondi, N. Desneux, G. Siscaro, L. Zappalà, Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: selectivity and side effects of 14 pesticides on the predator Orius laevigatus, Chemosphere 87 (2012) 803–812, https://doi.org/10.1016/j.chemosphere.2011.12.082.
[101] E.C. Barros, L. Bacci, M.C. Picanco, J.C. Martins, J.F. Rosado, G.A. Silva, Physiological selectivity and activity reduction of insecticides by rainfall to predatory wasps of *Tuta absoluta*, Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 50 (2015) 45–54, https://doi.org/10.1080/03601234.2015.965621.
[102] A. Joshi, R.B. Thapa, D. Kalauni, Integrated management of south AMERICAN tomato leaf miner [*Tuta absoluta* (meyrick)]: a review, Journal of the Plant Protection Society 5 (2018).
[103] R. Simkhada, R.B. Thapa, A.S.R. Bajracharya, R. Regmi, EFFICACY OF NOVEL INSECTICIDES AGAINST SOUTH AMERICAN TOMATO LEAF MINER (*Tuta absoluta* MEYRICK) UNDER PLASTIC HOUSE CONDITION IN KATHMANDU, Nepal, Journal of Agriculture and Forestry University 2 (2018) 133–140.
[104] M. Braham, L. Hajji, Management of *Tuta absoluta* (Lepidoptera, Gelechiidae) with insecticides on tomatoes, in: Agricultural and Biological Sciences, Insecticides-Pest Engineering, 2012, pp. 333–354. Croatia, https://books.google.com.np/books?hl=en&lr=&id=lCyaDwAAQBAJ&oi=fnd&pg=PA333&dq=Braham,+M. Croatia.
[105] M.M.M. Lietti, E. Botto, R.A. Alzogaray, Insecticide resistance in Argentine populations of *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae), Neotrop. Entomol. 34 (2005) 113–119, https://doi.org/10.1590/s1519-566x2005000100016.
[106] E. Roditakis, D. Steinbach, G. Moritz, E. Vasakis, M. Stavrakaki, A. Ilias, L. García-Vidal, M. del R. Martínez-Aguirre, P. Bielza, E. Morou, J.E. Silva, W.M. Silva, H.A.A. Siqueira, S. Iqbal, B.J. Troczka, M.S. Williamson, C. Bass, A. Tsagkarakou, J. Vontas, R. Nauen, Ryanodine receptor point mutations confer diamide insecticide resistance in tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae), Insect Biochem. Mol. Biol. 80 (2017) 11–20, https://doi.org/10.1016/j.ibmb.2016.11.003.
[107] NARC, NARC DIARY, 2019. https://narc.gov.np/wp-content/uploads/2020/07/NARC-Diary-2077.pdf.
[108] M.K. Kassa, Significant role of wild Genotypes of tomato trichomes for *Tuta absoluta* resistance, Journal of Plant Genetics and Breeding 2 (2018) 104.
[109] A. Domínguez, S. López, A. Bernabé, Á. Guerrero, C. Quero, Influence of age, host plant and mating status in pheromone production and new insights on perception plasticity in *Tuta absoluta*, Insects 10 (2019) 1–16, https://doi.org/10.3390/insects10080256.
[110] H.V.V. Tomé, E.M.G. Cordeiro, J.F. Rosado, R.N.C. Guedes, Egg exposure to pyriproxyfen in the tomato leaf miner *Tuta absoluta*: ovicidal activity or behavioural-modulated hatching mortality? Ann. Appl. Biol. 160 (2012) 35–42, https://doi.org/10.1111/j.1744-7348.2011.00518.x.
[111] M.R. El-Aassar, M.H.A. Soliman, A.A. Abd Elaal, Efficiency of sex pheromone traps and some bio and chemical insecticides against tomato borer larvae, *Tuta absoluta* (Meyrick) and estimate the damages of leaves and fruit tomato plant, Ann. Agric. Sci. (Cairo) 60 (2015) 153–156, https://doi.org/10.1016/j.aoas.2015.05.003.
[112] C.A. Faria, B.T. Torres, A.M. Fernandes, M.I. Farias, Parasitism of Tuta absoluta in Tomato Plants by Trichogramma Pretiosum Riley in Response to Host Density and Plant Structures Parasitismo, 38, Ciência Rural, Santa Maria, 2008, pp. 1504–1509, https://doi.org/10.1007/s40267-016-0369-3.
[113] F.L. Cônsoli, J.R.P. Parra, S.A. Hassan, Side-effects of insecticides used in tomato fields on the egg parasitoid *Trichogramma pretiosum* Riley (Hym., Trichogrammatidae), a natural enemy of *Tuta absoluta* (Meyrick) (Lep., Gelechiidae), J. Appl. Entomol. 122 (1998) 43–47, https://doi.org/10.1111/j.1439-0418.1998.tb01459.x.