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Review Article

A review on destructive tomato pest, *Phthorimaea absoluta* (Lepidoptera: Gelechiidae) and its management

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ABSTRACT: Tomato has extremely important health benefits which make it an important crop all around the world. Among several insect pests of tomato, *Phthorimaea absoluta* is the most devastating pest. This insect-pest has become one of the leading pests of tomato plants in recent years. The yield losses are often in the range of 80-100%. Larval stages of *Phthorimaea absoluta* are by far the most destructive stage of the insect because of its feeding habits. The neonate larvae feed on tomato fruits, leaves, flower buds and young shoots. Several chemical insecticides are used against this pest but resistance development to insecticides was reported. There is need of integrated pest management to control the pest population. This review discusses about the harmful effect of chemical pesticides and alternative methods to control *Phthorimaea absoluta* population. Different methods of pest control include botanical control, biological control and new emerging techniques of green synthesized nanoparticles.

KEYWORDS: Fecundity, invasive pest, IPM, mortality, nanoparticles

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INTRODUCTION

The agricultural sector contributes 6.4% of the total global economic production as well as being a valuable sector in many areas. Due to the rapid growth in the human population, this sector faces tremendous challenges. It is forecasted that the total world population will be between 8 and 10 billion people by 2050, which means nutritious foods will be necessary to feed them (Mattoo, 2014; Martin and Li, 2017; Roberts and Mattoo, 2019). In terms of nutritional value, tomatoes are the most often consumed edible vegetable crops (a rich source of vitamin A, B and C) and they are used as a source of income for the farmers as well. It has been shown that tomato fruit consumption is associated with a lower risk of inflammation, cancer and chronic noncommunicable diseases. Additionally, it can also help to reduce the risk of heart disease, diabetes and obesity as well as high blood pressure (Raiola *et al.*, 2014). Tomato is ranked sixth among the 15 vegetables recognized by the FAO (Food and Agriculture Organization) in terms of total annual global output.

Every part of the plant can serve as a food source, shelter and reproductive site for insect pests. Major insect-pests that attack tomato crops are *Helicoverpa armigera* Hubner (fruit borer), *Spodoptera exigua* Hubner (army worm), *Bemisia tabaci* Gennadius (Whitefly), *Liriomyza trifolii* Burgess (leafminer) and *Tetranychus cinnabarinus* Boisdual (Spider mites) (Nagaraju *et al.*, 2002; Sanju and Saxena, 2020). Tomato crop is infested by different insect-pests but *Phthorimaea absoluta* (tomato leafminer) a Lepidopteran of Gelechiidae family (Desneux *et al.*, 2010) is most harmful and deleterious insect-pest of Solanaceous crops (mostly tomatoes). *T. absoluta*, leafminer affect other Solanaceous

crops like potato, eggplant, pepper and pepino (Desneux *et al.*, 2010; Mohamed *et al.*, 2015). In agrochemical condition, *Phthorimaea absoluta* emerges rapidly and it is considered a pest species that spreads rapidly causing economic damage as well as nutritional problems to the tomato crop (Desneux *et al.*, 2010).

Tomato leafminer is a South American insect-pest and first discovered in its natural area in Spain (2006) (Desneux *et al.*, 2010). In India, *Phthorimaea absoluta* was firstly detected from Pune (Maharastra) during October (ICAR 2014) and also recorded in different states of India (Shashank *et al.*, 2016). In recent years it has spread to many countries around the globe and has now become a serious pest of greenhouse and outdoor crops as a result of its invasion (Sridhar, Chakravarthy and Asokan, 2014). It is believed that packaging materials from infested countries could be one of the main reasons for the long-distance spread of tomato leafminer. As an insect, it spread illness from one plant part to another by creating mines, as well as significantly influencing the quality and yield of fruits (Kaoud *et al.*, 2019). Due to the larvae's ability to feed on every part of the tomato crop, they do extensive damage to it. Depending on the climatic conditions, the fecundity of tomato leafminers is high, with a life cycle of 30-35 days depending on the climatic conditions (Harizanova, Stoeva and Mohamedova, 2009). In order to invade tomato plants, *Phthorimaea absoluta* uses a unique method of invading the plant parts. As a result, chemical pesticides are being used to prevent epidemics from spreading in newly invaded areas, but chemical pesticides are known to cause serious health problems so that alternative methods such as biological controls (virus, entomopathogenic nematodes), use of semiochemicals, botanicals are required to prevent this insect-pest.

Phthorimaea absoluta, a native of South America tomato pinworm, is an intrusive insect-pest species. Meyrick (1917) initially described this pest as *Phthorimaea absolut*a (1917), from a male specimen which is accumulated in the Andean region of Peru. In European region, *Phthorimaea absoluta* was firstly detected at Eastern region of Spain in 2006 and is currently spreading around the world (Ferracini *et al.*, 2019). Between 2006 and 2012 this pest quickly expanded over the Mediterranean Basic (Garzia *et al.*, 2012). Originally found in Spain, this pest has now extended to numerous European nations such as Italy (2008), France (2008), Albania (2009), Bulgaria (2009), Portugal (2009), Netherlands (2009), United Kingdom (2009) and Serbia (2011) (Desneux *et al.*, 2011). In India, *Phthorimaea absoluta* for the first time detected from Pune (Maharastra) during October (ICAR 2014) and this pest is also recorded in different states of India (Shashank *et al.*, 2016). *Phthorimaea absoluta* was discovered infesting tomato and potato plants (Solanaceous crops) in the Hyderabad-Karnataka regions in India (Kalleshwaraswamy, Shankara and Krishna, 2021), in January and February 2015. For the first time, Department of Entomology, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan of Himachal Pradesh, India, has employed survey visit in experimental farm of university in tomato crop in November month, leaves with large, irregular, blotch-like mines were spotted for the first time (Sharma and Gavkare, 2017). It is the first time of *Phthorimaea absoluta* has appeared on a tomato plant Himachal Pradesh's mid-hill, in the North-western Himalayan area.

Biology and life cycle of *Phthorimaea absoluta* (Tomato Leafminer)

Phthorimaea absoluta is regarded as typically invasive insect-pest species because of its ability to grow very fast in favourable agro-economically environment, spread swiftly to new regions and cause economically significant harm (Desneux *et al.*, 2010). Tomato leafminer is a multivoltine (having two or more broods of offspring per year) insect species which have strong fecundity, that allow the pest population to swiftly grow (Pereyra and Sánchez, 2006; Garzia *et al.*, 2012)tomato (*Lycopersicum esculentum* Mill. Upon emergence from their eggs in the morning, the larvae move around for about five to forty minutes before they begin to mine the plant. 1st-2nd young larval instars burrow inside the plant and after maturing 3rd-4th larval instars abandon their mines to migrate another site. *Phthorimaea absoluta*'s larva forms uneven mines on the leaf surface and fruits as a result of this feeding habit, reducing the plant's capacity to protect itself against hazardous chemicals (Biondi *et al.*, 2018) (Fig. 1). If the climatic conditions are favorable and the larvae have access to adequate food, they will continuously feed on the plant and will not enter a diapause state. Pupation takes place mostly on leaves, fruits and in the soil, depending on environmental and growth circumstances, with a small fraction occurring in other protected locations such as stems and fruits (Viggiani *et al.*, 2009; Garzia *et al.*, 2012). The pupa turns dark brown after about 5 days at 30 degree celsius, and adult is ready for emergence (Monserrat Delgado, 2008). A review of *Phthorimaea absoluta's* biology and ecology for the African and Eurasian region (Biondi *et al.*, 2018), the Mediterranean Basin (Giorgini *et al.*, 2019) increasing temperatures due to climatic change exacerbate this problem by allowing pests to further reach regions previously considered unsuitable. The tomato pinworm *T. absoluta* (Meyrick and Africa (Mansour *et al.*, 2018) offered substantial details of the pest as well as its worldwide distribution. The result of direct damage as well as indirect damage has been reported to be a loss of yield of 50-100% (Desneux *et al.*, 2010).

Based on both the laboratory and net house tests performed by ICAR-NBAIR, it can be concluded that under Bengaluru conditions, the pest has a life cycle of 21-23 days (Ballal *et al.*, 2016). There was a difference in the larval development of *T. absoluta* on tomato plants in comparison with other plants. Larval development was the fastest (15.1 days) on tomato leaves followed by potato leaves, tomato fruits, brinjal leaves, pepino leaves and potato tuber. Similarly, the pupal period was longest (10.4 days) on tomato leaves and shortest on potato tubers, pepino and brinjal leaves (Negi *et al.*, 2018). In Northeast state (Meghalaya) *T. absoluta* infestation increased from January to April and this may be due to a combination of host suitability and a rise in temperature between January and April, which could have an effect on infestation rates (Sankarganesh *et al.*, 2017).

Over 80% of tomato crops in Nigeria were destroyed by *Phthorimaea absoluta* and prompting the Nigerian government to declare emergency following the invasion of tomato pinworm (Borisade *et al.,* 2017).The temperature threshold of *T. absoluta* survival is of wide range, ranging between 8-35 degree celsius (Krechemer and Foerster, 2015; Fand *et al.,* 2020). As far as *Phthorimaea* was concerned, cultivated tomatoes had an absolute advantage over wild varieties of tomatoes. (Proffit *et al*., 2011). In addition Female T. *absoluta* prefer tomato plants over potato plants (Caparros Megido *et al*., 2014). All laboratory experiments showed that the major host of tomato leafminer is cultivated tomatoes. As compared to other plant species, this insect-pest species has a greater global fitness on this specific host (Negi *et al.,* 2018; Cherif and Verheggen, 2019; Cherif *et al.,* 2019).

Integrated Pest Management (IPM)

Integrated Pest Management is an approach that is aimed at keeping crops healthy without the use of chemical pesticides. There are many management techniques and strategies that can be integrated into an IPM program to ensure crop conservation on an ecosystem level. There is a need to reduce the negative impact of chemical pesticides such as resistance, other side effects, and harm to the environment, professionals came up with the idea of IPM in the 1960s (FAO 2003). The idea of Integrated Pest Management (IPM) is based on the fact that a healthy crop may be maintained in an environment where the biological processes are flourished

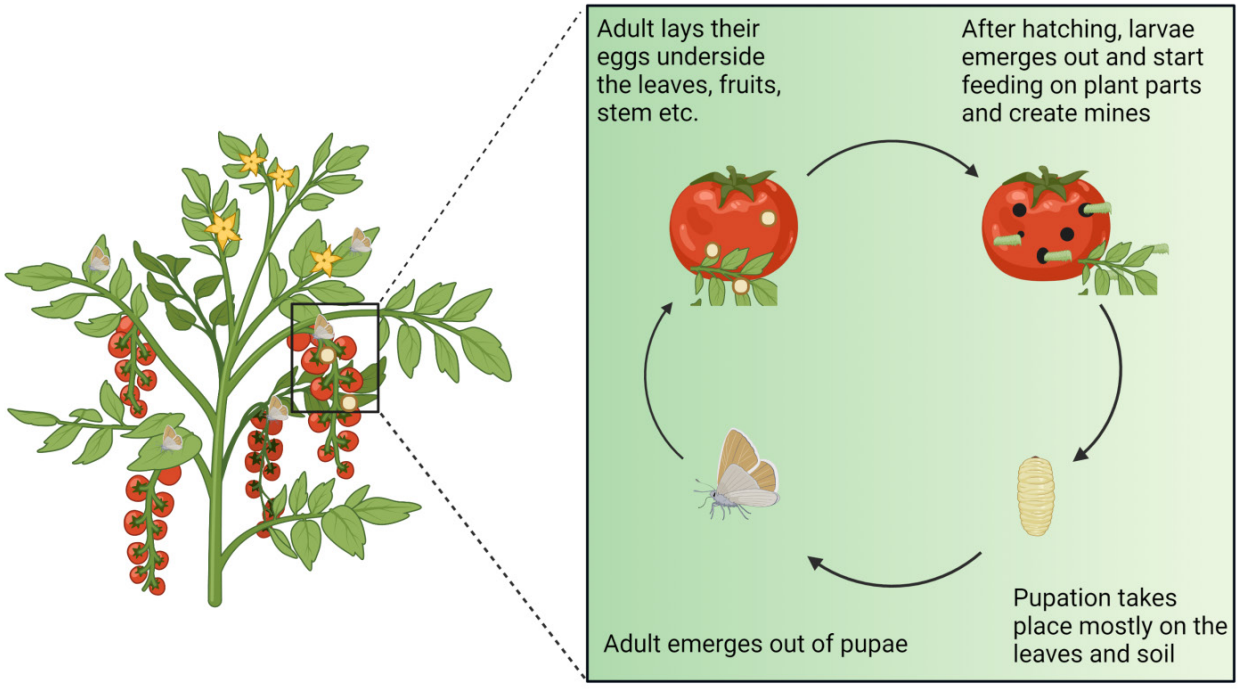

Figure 1. Life cycle of *Phthorimaea absoluta* showing different metamorphic stages, adult *Phthorimaea absoluta* laid their eggs underside the leaves, inside the fruit, stem etc. After hatching, larvae emerge out and start feeding on the plant parts. Mating of adults and their survival period is between 7-15 days. Eggs laid on the underside of leaf and hatching period takes 4-5 days. The larva feeds on the leaf mesophyll tissue, development of larval instars takes 11 days. Maturing pupa and its development periods takes 8-9 days.

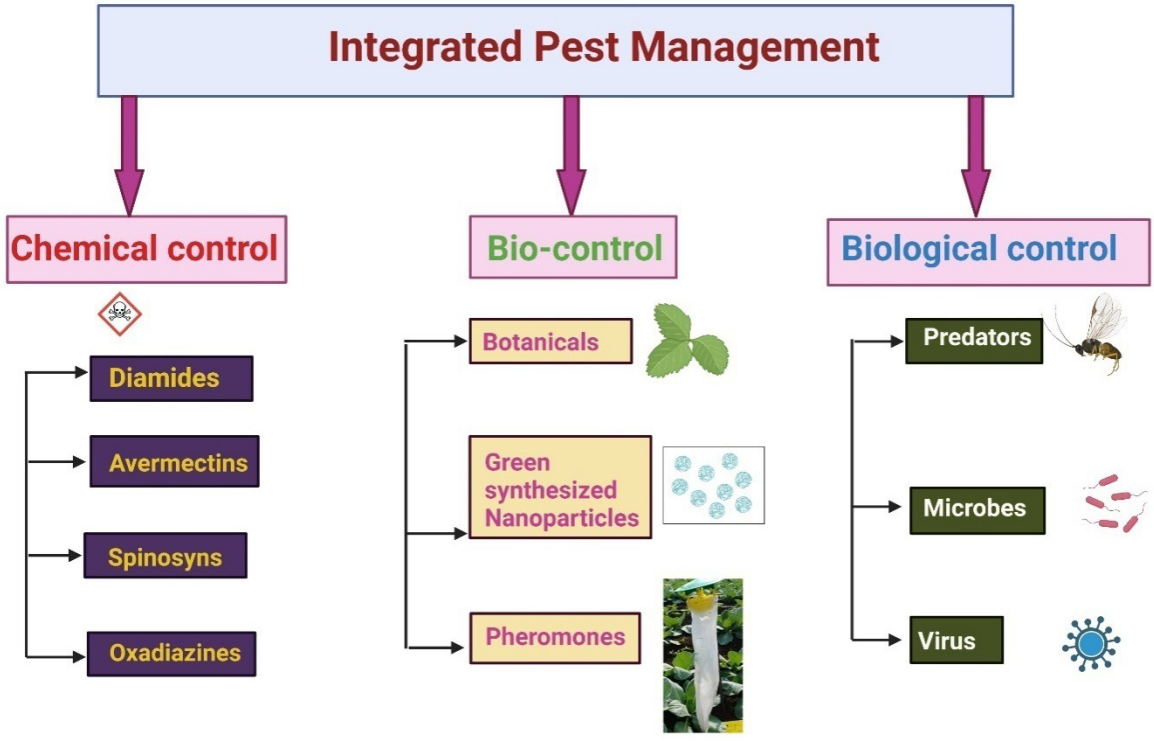

Figure 2. Techniques of IPM: Chemical control, biocontrol and biological control. Chemical control includes diamides, avermectins, spinosyns, oxidiazines. Biocontrol includes uses of botanicals, sex-pheromones and green synthesized nanoparticles. Biological control includes microbial (*Bacillus thurinigensis*), viruses (*Baculovirus*) and *predators*.

and improved for the crop to retain its health (FAO 2011) (Figure 2).

Chemical control

There are different chemicals that are used in the control of *Phthorimaea absoluta*. Around the world, insecticides and pesticides remain the most influential tools for the control of insects and pests (Guedes *et al.*, 2019) *Phthorimaea absoluta* (Meyrick). Pesticides from several synthetics with distinct ways of action, like diamides, avermectins, spinosyns and oxadiazines are used to manage *T. absoluta* in Mediterranean areas (Roditakis *et al.*, 2018). Chemical active substances combo (Chloratraniliprole + abamectin) sprayed at 60 mL/hL in the monastir area of Center East Tunisia was successful in suppressing *T. absoluta* in glasshouse tomato crops (Braham and Hajji, 2012). Most frequent way to control *T. absoluta* is the use of insecticides that are injurious to human health and environment (Guedes *et al.*, 1994; Picanço *et al.*, 1998; Derbalah, Morsey and El-Samahy, 2012). Chemical control efficacy is limited because of insect's unique method of damage causing potential and capacity to build resistance against pesticides (Siqueira, Guedes and Picanço, 2000; Lietti, Botto and Alzogaray, 2005).

Phthorimaea absoluta exhibiting resistance to different pesticides

Phthorimaea absoluta has developed a pesticide resistance, which has been examined in numerous examples (Crespo *et al.*, 2011; Silva *et al.*, 2016). Diamides offer a good control of the *T. absoluta* population, but Germany reported first incidence of resistance of diamides in European greenhouses (Roditakis and Vasakis, 2015). There were insecticidal products released during 1990s, including abamectin, acylurea, spinosad, tebufenozide and chlorfenapyr (Galarza and Larroque, 1984). Resistance towards organophosphates and pyrethroids have been found in Chile (Salazar and Araya, 2001) and Brazil (Siqueira *et al.*, 2001) respectively. Different activities performed by insect-pest such as detoxification enzymes, insensitivity to target site and increased excretion leads to the resistance against pesticides. Chemical control methods are disturbing tomato crop IPM programs in several Mediterranean locations (Zappalà *et al.*, 2012) (Croft, 1990; Desneux, Decourtye and Delpuech, 2007). Side effects of pesticides declines the natural enemies like predator's population of different pests of tomato.

Biological control

As invasive species have become a global threat in the past half century, they have resulted in dramatic changes to thriving and diverse ecosystems around the world. As a means of combating this problem, bio-control is considered to be one of the most important strategies in addition to manual, mechanical removal and chemical methods.

Phthorimaea absoluta has unique pattern of feeding. It creates mines in fruits, leaves and stems, so we need an alternative control methods of pest control. It also develops resistance against several insecticides. Biopesticides are highly efficient in agricultural pest management without endangering the ecological chain or raising pollution levels. The development of effective biopesticide applications substantially reduces environmental pollution by chemical pesticide and enhances agriculture's long-term sustainability (Leng *et al.*, 2011). The positive performance of the validated IPM package composed of *Bacillus thuringiensis*, *Bacillus bassiana*, neem and chlorantraniliprole along with installation of pheromone traps were showed great results against *T. absoluta* (Buragohain *et al.*, 2021).

Use of bioagents

In Europe researchers investigated that *Trichogramma* species are effectively used against *Phthorimaea absoluta* (Cabello *et al.*, 2012; Chailleux *et al.*, 2013). Predator such as *Macrolophus pygmaeus* Wagner and *Nesidiocoris tenuis* Reuter, are mostly used to prevent tomatoes grown in greenhouses from whiteflies (Bonato, Couton and Fargues, 2006; Nannini *et al.*, 2007; Chailleux *et al.*, 2013). And these predators of *T. absoluta's* attacks on leafminer eggs (Calvo *et al.*, 2012; Chailleux *et al.*, 2013). The employment of arthropod natural enemies or microbial compounds can help to control the population of tomato pinworm, in Europe (Desneux *et al.*, 2010; Zappala *et al.*, 2013), the predator such as *Nesidiocoris tenuis* has showed such a great promise in reducing the *T. absoluta* population in Asia. It was found that a large population of the mirid bug *Nesidiocoris tenuis* (Reuter) was associated with *T. absoluta* in all the fields. On tomato crops, especially in the Mediterranean region, this predator is widely used as a major natural enemy of a variety of insects (including the pest *T. absoluta*).

Microbial control

A spore forming bacteria *Bacillus* is a diverse group of bacteria; consists of more than 20 species It is found in terrestrial habitat, soil, dead insects and on plants (American Academy of Microbiology, 2002). *B. thuringiensis* is eaten. The bacteria produce both spores and endotoxins (crystalline protein). When this is consumed by larva of insects, crystalline protein becomes activated and binds to the gut of insect creating a pore through which it enters to the body cavity and bloodstream. After intake insect dies within few days (Tabashnik *et al.*, 2003). Population dynamics of insect-pest can be evaluated by study of age, life cycle, sex life table and stages of differentiation (Chi and Liu, 1985; Chi, 1988) (Ballal *et al.*, 2016). Spinosad (chemical compound found in bacterial species) is another biological control agent with little toxicity for mammals, birds, insects and predators, as well as no risk to users and largest impact is on insect's orders for example, Lepidopteran, Diptera, Thysanoptera, Coleoptera and Orhtoptera (Toews, Subramanyam and Rowan, 2003). Both the nicotine acetylcholine receptor and the GABA receptor were affected by Spinosad (Watson *et al.*, 2010).

Virus control

A group of *Baculoviridae* family that infect insect species from Dipteran, Hymenoptera and Lepidopteran orders (Rohrman, 2011). These pathogens have two different phenotypes during their life cycle in hosts: occlusion bodies and budded viruses, which are surrounded by crystalline protein structures. In Colombia, *Phthorimaea absoluta* cause serious damage to tomato crops in greenhouses. In this *Baculovirus* act as interesting active ingredient for bio-pesticides (Haase, Sciocco-Cap and Romanowski, 2015).

Botanicals

Botanicals are extracts of plants, natural oils and plant volatiles which have pest control activities (Regnault-Roger and Philogène, 2008). For example, Neem a combination of leaves, seeds and bark extricate from an evergreen endless tree which is indigenous to Asia continent. The *Azadirachta indica* includes a bitter compound that act as a growth regulator as well as deterrent to feeding, keeps insect away from crop. Fresh or dried portions of the plants are used to extract the active compounds using alcohol, water or other solvents (Trucksess and Scott, 2008). In ancient times, Egyptians dynasties used botanicals as pesticides (Isman, 2006). Marigold extracts, Mandarin crust oil, camphor oil has been tested against *Phthorimaea absoluta* shows great mortality (Marouf and Harras, 2022). A laboratory study was conducted to test the insecticidal effects of seven plants (*Thymus vulgaris*, *Ricinus communis*, *Ononis natrix*, *Peganum harmala*, *Argania spinosa*, *Urtica dioica* and *Lawsonia inermis*) collected and used against the larvae of the *T. absoluta* shows positive results.

Glycoalkaloids are the secondary metabolites mostly found in plants. These plant metabolites can be used against *T. absoluta* control. Because alkaloids are commonly found in unripe fruits, large quantities of them may discourage herbivores from eating. Weissenberg examined glycoalkaloids

such as solamargine and solasonine on *Tribolium castaneum*, which belongs to the same family (Tenebrionidae) as *T. molitor* (Weissenberg *et al.*, 1998). *S. nigrum* extract that has been shown to have potential of anti-cancerous property (Patel *et al.*, 2009). In the field of integrated pest management use of plant extracts can be a potential approach.

Now-a-days, botanicals in pest control are receiving great attention, because they are safer and used as an alternative (Regnault-Roger and Philogène, 2008).

Green synthesized nanoparticles

Green synthesized metal nanoparticles are a good tool for controlling agricultural pests both in open and protected fields. Iron oxide nanoparticles (FeNP) derived from *Trigonella foenum-graecum* leaf extract is effective against *T. a*bsoluta at very low concentration (Ramkumar *et al.*, 2021). Currently, researchers have established that it is economical to synthesize bio-NPs from plants, yeasts, algae and fungi since they are reliable, cost-effective, capable, straight forward and easily available sources of natural resources. The development of efficient nanomaterials has been explored using a variety of approaches by scientists. Citrus peel essential oils were tested against the invasive tomato pest. The lethal and sublethal activity of citrus peel EOs as Emulsion and nanoparticles (EO-NPs) formulations were determined against the invasive tomato pest *Phthorimaea absoluta* shows remarkable result (Campolo *et al.*, 2017). The study suggests that these natural compounds (obtained from plant extracts), especially when they are nanoformulated, could be used in integrated pest management programs for the control of *T. absoluta* in order to counteract the adverse effects of this pest.

Semiochemicals

Sex pheromones have comprehensively been used to control *Phthorimaea absoluta* pest (Prasad and Prabhakar, 2012). Adult female mostly release chemical signal to attract opposite sex for mating (Caparros Megido, Haubruge and Verheggen, 2013). Pheromones-induced and kill, mass trapping and interruption of mating behaviours are all examples of semiochemical-based insect control (Cocco, Deliperi and Delrio, 2013). Pheromones-based control of *Phthorimaea absoluta* is best used as a Integrated Pest Management approaches. For example, a research in Egypt found that combining sex-pheromones with other pesticides is effective against *T. absoluta* larva (El-Aassar, Soliman and Abd Elaal, 2015).

CONCLUSION

In the agriculture sector, pest control is one of the most challenging issues. There is an urgent need for effective and safe methods of pest control throughout the world. *Phthorimaea absoluta* is a pest that is most noticeable in tomatoes and other crops in the solanaceous family. A number of control measures have been attempted and developed against this insect in the past. Among the several methods of pest control that are available, chemical insecticides, microbial control, virus control, semiochemicals and botanical remedies are among the most common. Several specific pest control methods have been developed over the past several decades, along with the development of a comprehensive management system, known as integrated pest management. The biological methods coupled with botanicals and pheromone application may bring down the *Phthorimaea* population in tomato fields. As an effective insecticide, plant-derived nano-pesticides play a remarkable role. More studies are needed to derive active ingredients from plants for the green synthesized nanoparticles.

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AUTHOR CONTRIBUTION

SK: Conceptualization; KC: Data Analysis, Curation and Validation; KR, JY, KT: Data Interpretation and Literature Review, KC: Original Draft Preparation; DS and SK: Editing, Final Draft Preparation and Critical Revision.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

Ballal CR, *et al.* 2016. The new invasive pest *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae) in India and its natural enemies along with evaluation of trichogrammatids for its biological control. *Cur. Sci.* **110**(11):2155–2159. https://doi.org/10.18520/cs/v110/i11/2155-2159

Biondi A. *et al.* 2018. Ecology, worldwide spread and management of the invasive south american tomato pinworm, *Phthorimaea absoluta*: Past, Present, and Future'. *Annu. Rev. Entomol*. **63**:239–258. PMid: 28977774. https://doi.org/10.1146/annurev-ento-031616-034933

Bonato O, Couton L, and Fargues J. 2006. Feeding preference of *Macrolophus caliginosus* (Heteroptera:Miridae) on *Bemisia tabaci* and *Trialeurodes vaporariorum*

(Homoptera:Aleyrodidae). *J. Econ. Entomol*. **99**(4):1143–1151. PMid: 16937666. https://doi.org/10.1603/0022-0493-99.4.1143

Borisade OA, *et al.* 2017. The tomato leafminer (*Phthorimaea absoluta*) (Lepidoptera:Gelechiidae) attack in Nigeria: Effect of climate change on over-sighted pest or agro-bioterrorism? *J. Agric. Ext. Rural Dev*, **9**(8):163–171. https://doi.org/10.5897/jaerd2017.0856

Braham M, and Hajji L. 2012. Management of *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) with insecticides on tomatoes. *eka Croatia,* Insecticides-Pest Engineering, Tech, Rijeka, *Croatia*. 333–354. https://doi.org/10.5772/27812

Buragohain P, *et al.* 2021. Development and validation of an integrated pest management strategy against the invasive South American tomato leafminer, *Phthorimaea absoluta* in South India. *J. Crop Prot.* **139**:105348. https://doi.org/10.1016/j.cropro.2020.105348

Cabello T, *et al.* 2012. Biological control strategies for the South American tomato moth (Lepidoptera:Gelechiidae) in greenhouse tomatoes. *J. Econ. Entomol*. **105**(6):2085–2096. PMid: 23356074. https://doi.org/10.1603/EC12221

Calvo FJ, *et al.* 2012. Preplant release of *Nesidiocoris tenuis* and supplementary tactics for control of *Phthorimaea absoluta* and *Bemisa tabaci* in greenhouse tomato. *Entomol. Exp. Appl.*. **143**(2):111–119. https://doi.org/10.1111/j.1570-7458.2012.01238.x

Campolo O, *et al.* 2017. Citrus peel essential oil nanoformulations to control the tomato borer, *Phthorimaea absoluta*: Chemical properties and biological activity. *Sci. Rep.* **7**(1):1–10. PMid: 29026207 PMCid: PMC5638903. https://doi.org/10.1038/s41598-017-13413-0.

Caparros Megido R, *et al.* 2014. Role of larval host plant experience and solanaceous plant volatile emissions in *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) host finding behavior. *Arthropod Plant Interact*. **8**(4):293–304. https://doi.org/10.1007/s11829-014-9315-2.

Caparros Megido R, Haubruge E, and Verheggen FJ. 2013. Pheromone-based management strategies to control the tomato leafminer, *Phthorimaea absoluta* (Lepidoptera:Gelechiidae). A review | Synthèse bibliographique: Les stratégies de lutte phéromonale utilisées pour contrôler la mineuse de la tomate, *Phthorimaea absoluta* (Lepi). *Biotechnol. Agron. Soc. Environ*. **17**(3):475–482.

Chailleux A, *et al.* 2013. Potential for combined use of parasitoids and generalist predators for biological control of the key invasive tomato pest *Phthorimaea absoluta. J Pest Sci.* **86**(3):533–541. https://doi.org/10.1007/s10340-013-0498-6

Cherif A, *et al.* 2019. Elucidating key biological parameters of *Phthorimaea absoluta* on different host plants and under various temperature and relative humidity regimes. *Entomol. Gen.* **39**(1):1–7. https://doi.org/10.1127/entomologia/2019/0685

Cherif A, and Verheggen F. 2019. A review of *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) host plants and their impact on management strategies. *Biotechnol. Agron. Soc. Environ.* **23**(4):270–278. https://doi.org/10.25518/1780-4507.18211

Chi H. 1988. Life-table analysis incorporating both sexes and variable development rates among individuals. *Environ. Entomol*. **17**(1):26–34. https://doi.org/10.1093/ee/17.1.26

Chi H, and Liu HSI. 1985. Two new methods for the study of insect population ecology. *Bull. Inst. Zool. Acad. Sin*. **24**(2):225–240.

Cocco A, Deliperi S, and Delrio G. 2013. Control of *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae) in greenhouse tomato crops using the mating disruption technique. *J. Appl. Entomol.* **137**(1-2):16–28. Available at: https://doi.org/10.1111/j.1439-0418.2012.01735.x

Crespo LB, *et al.* 2011. Control failure likelihood and spatial dependence of insecticide resistance in the tomato pinworm, *Phthorimaea absoluta* Jander F Rosado and Raul Narciso C Guedes (August 2010). 913–920. PMid: 21394881. https://doi.org/10.1002/ps.2131

Croft BA. 1990. Arthropod biological control agents and pesticides. John Wiley and Sons Inc.

Derbalah AS, Morsey SZ, and El-Samahy M. 2012. Some recent approaches to control *Phthorimaea absoluta* in tomato under greenhouse conditions. *Afr. Entomol*. **20**(1):27–34. https://doi.org/10.4001/003.020.0104

Desneux N, *et al.* 2010. Biological invasion of European tomato crops by *Phthorimaea absoluta*: ecology, geographic expansion and prospects for biological control. *J Pest Sci*. **83**:197–15. https://doi.org/10.1007/s10340-010-0321-6

Desneux, N. *et al.* 2011. The invasive South American tomato pinworm, *Phthorimaea absoluta*, continues to spread

in Afro-Eurasia and beyond: the new threat to tomato world production. *J Pest Sci*. **84**(4):403–408. https://doi.org/10.1007/s10340-011-0398-6

Desneux N, Decourtye A, and Delpuech JM. 2007. The sublethal effects of pesticides on beneficial arthropods. *Annu. Rev. Entomol.* **52**:81–106. PMid: 16842032. https://doi.org/10.1146/annurev.ento.52.110405.091440

El-Aassar MR, Soliman MHA, and Abd Elaal AA. 2015. Efficiency of sex pheromone traps and some bio and chemical insecticides against tomato borer larvae, *Phthorimaea absoluta* (Meyrick) and estimate the damages of leaves and fruit tomato plant. *Ann. Agric. Sci*. **60**(1):153–156. https://doi.org/10.1016/j.aoas.2015.05.003

Fand BB, *et al.* 2020. Invasion risk of the South American tomato pinworm *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae) in India: predictions based on MaxEnt ecological niche modeling. *Int. J. Trop. Insect Sci.* [Preprint]. Available at: https://doi.org/10.1007/s42690-020-00103-0

Ferracini C, *et al.* 2019. Natural enemies of *Phthorimaea absoluta* in the Mediterranean basin. Europe and South America. *Biocontrol Sci. Technol*. **29**(6):578–609. https://doi.org/10.1080/09583157.2019.1572711

Galarza J, and Larroque O. 1984. Control de *Scrobipalpula absoluta* (Meyr.) (Lepidoptera:Gelechidae) en tomate. *IDIA*. **421**:15–18.

Garzia GT, *et al.* 2012. *Phthorimaea absoluta*, a South American pest of tomato now in the EPPO region: biology, distribution and damage. *Wiley Online Library.* **42**(2):205–210. https://doi.org/10.1111/epp.2556.

Giorgini M, *et al.* 2019. Current strategies and future outlook for managing the neotropical –tomato pest *Phthorimaea absoluta* (Meyrick) in the Mediterranean Basin. *Neotrop. Entomol.* **48**:1–17. PMid: 30284151. https://doi.org/10.1007/s13744-018-0636-1

Guedes RNC, *et al.* 1994. Efeito de inseticidas e sistemas de condução do tomateiro no controle de *Scrobipalpuloides absoluta* (Meyrick) (Lepidoptera: Gelechiidae). https://doi.org/10.37486/0301-8059.v23i2.946

Guedes RNC, *et al.* 2019. Insecticide resistance in the tomato pinworm *Phthorimaea absoluta*: patterns, spread, mechanisms, management and outlook. *J Pest Sci*., **92**(4):1329–1342. https://doi.org/10.1007/s10340-019-01086-9

Haase S, Sciocco-Cap A, and Romanowski V. 2015. Baculovirus insecticides in Latin America: historical overview, current status and future perspectives. *Viruses*. **7**(5):2230–2267. PMid: 25941826 PMCid: PMC4452904. https://doi.org/10.3390/v7052230

Harizanova V, Stoeva A, and Mohamedova M. 2009. Tomato leafminer, *Phthorimaea absoluta* (Povolny) (Lepidoptera:Gelechiidae) - first record in Bulgaria. January.

Isman MB. 2006. Botanical insecticides, deterrents and repellents in modern agriculture and an increasingly regulated world, *Annu. Rev. Entomol.* **51**:45–66. PMid: 16332203, https://doi.org/10.1146/annurev.ento.51.110104.151146

Kalleshwaraswamy A, Shankara M, and Krishna NK. 2021. Occurrence of *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) in the Malnad and Hyderabad-Karnataka Regions of Occurrence of *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) in the Malnad and Hyderabad-Karnataka Regions of Karnataka, India.

Kaoud H, *et al.* 2019. *Phthorimaea absoluta*, a South American pest of tomato now in the EPPO region: Biology, distribution and damage. *J. Pest Sci.* **92**(4):9–16. https://doi.org/10.1007/s10340-015-0643-5

Krechemer F da S, and Foerster LA. 2015. *Phthorimaea absoluta* (Lepidoptera:Gelechiidae): Thermal requirements and effect of temperature on development, survival, reproduction and longevity. *Eur. J. Entomol.* **112**(4):658–663. https://doi.org/10.14411/eje.2015.103

Leng P, *et al.* 2011. Applications and development trends in biopesticides. *Afr. J. Biotechnol.* **10**(86):19864–19873. https://doi.org/10.5897/AJBX11.009

Lietti MMM, Botto E, Alzogaray RA. 2005. Insecticide resistance in argentine populations of *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae). *Neotrop. Entomol*. **34**:113–119. https://doi.org/10.1590/S1519-566X2005000100016

Mansour, R. *et al.* 2018. Occurrence, biology, natural enemies and management of Phthorimaeaabsoluta in Africa. *Entomol. Gen*. **38**(2):83–112. https://doi.org/10.1127/entomologia/2018/0749

Maroufa A, and Harras F. 2022. Efficacy of three plant oil extracts and their nano-emulsions on the leafminer, *Phthorimaea absoluta* Larvae (Meyrick) (Lepidoptera:Gelechiidae*)*.

J. Plant Prot. & Pathol. **13**(9):207–213. https://doi.org/10.21608/jppp.2022.153798.1090

Martin C, Li J. 2017. Medicine is not health care, food is health care: Plant metabolic engineering, diet and human health. *New Phytol*. **216**(3):699–719. PMid: 28796289. https://doi.org/10.1111/nph.14730

Mattoo AK. 2014. Translational research in agricultural biology-enhancing crop resistivity against environmental stress alongside nutritional quality. *Front. Chem.* **2**(Jun):1–9. PMid: 24926479 PMCid: PMC4046571. https://doi.org/10.3389/fchem.2014.00030

Mohamed ESI, *et al.* 2015. Host plants record for tomato leafminer *Phthorimaea absoluta* (Meyrick) in Sudan. *Wiley Online Library*. **45**:108–111. https://doi.org/10.1111/epp.12178

Monserrat Delgado A. 2008. The South American tomato pinworm (*Phthorimaea absoluta*) in the Murcia Region: bases for its control. Consejerıa de Agricultura y Agua, Región de Murcia (in Spanish) [Preprint].

Nagaraju N, *et al.* 2002. Farmers' perceptions and practices for managing tomato leaf curl virus disease in southern India. *Int. J. Pest Manag*. **4**8(4):333–338. https://doi.org/10.1080/09670870210153164

Nannini M, *et al.* 2007. Natural enemies for tomato pest control in Sardinian greenhouses. *Acta Hortic*. **747**:415-423. https://doi.org/10.17660/ActaHortic.2007.747.52

Negi S, *et al.* 2018. Effect of host plants on developmental and population parameters of invasive leafminer, *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae). *Phytoparasitica*. **46**(2):213–221. https://doi.org/10.1007/s12600-018-0661-y

Patel S, *et al.* 2009. In-vitro cytotoxicity activity of *Solanum nigrum* extract against Hela cell line and Vero cell line. *Int. J. Pharm. Pharm. Sci.* **1**(Suppl. 1):38–46.

Pereyra PC, and Sánchez NE. 2006. Effect of two solanaceous plants on developmental and population parameters of the tomato leafminer, *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae). *Neotrop. Entomol.* **35**(5):671–676. PMid: 17144141. https://doi.org/10.1590/S1519-566X2006000500016

Picanco M, *et al.* 1998. Yield loss in trellised tomato affected by insecticidal sprays and plant spacing. *J. Crop Prot.* **17**(5):447–452. https://doi.org/10.1016/S0261-2194(98)00040-4

Prasad YG, and Prabhakar M. 2012. Pest monitoring and forecasting. *IPM. Principles and Practice*. May, pp. 41–57. https://doi.org/10.1079/9781845938086.0041

Proffit M, *et al.* 2011.Attraction and Oviposition of *Phthorimaea absoluta* females in response to tomato leaf volatiles, *J. Chem. Ecol*. **37**(6):565–574. PMid: 21559877. https://doi.org/10.1007/s10886-011-9961-0

Raiola A, *et al.* 2014. Enhancing the health-promoting effects of tomato fruit for biofortified food. 2014. PMid: 24744504 PMCid: PMC3972926. https://doi.org/10.1155/2014/139873

Ramkumar G, *et al.* 2021. Characterization of Trigonella foenum-graecum derived Iron nanoparticles and its potential pesticidal activity against *Phthorimaea absoluta* (Lepidoptera). *J. Clust. Sci*. **32**(5):1185–1190. https://doi.org/10.1007/s10876-020-01867-8

Regnault-Roger C, and Philogène BJR. 2008. Past and current prospects for the use of botanicals and plant allelochemicals in integrated pest management. *Pharm. Biol.* **46**(1-2):41–52. https://doi.org/10.1080/13880200701729794

Roberts DP, and Mattoo AK. 2019. Sustainable crop production systems and human nutrition. *Frontiers in Sustainable Food Systems.* **3**(Sept):1–14. https://doi.org/10.3389/fsufs.2019.00072

Roditakis E, *et al.* 2018. A four-year survey on insecticide resistance and likelihood of chemical control failure for tomato leafminer *Phthorimaea absoluta* in the European/Asian region. *J. Pest Sci.* **91**(1):421–435. https://doi.org/10.1007/s10340-017-0900-x

Roditakis E, and Vasakis E. 2015. First report of *Phthorimaea absoluta* resistance to diamide insecticides. *J. Pest Sci*. **88**:9-16. https://doi.org/10.1007/s10340-015-0643-5

Rohrman, G.F. 2011. Baculovirus molecular biology, 2nd edn (Internet), Bethesda, MD: *National Center for Biotechnology Information* [Preprint].

Salazar ER, and Araya JE. 2001. Respuesta de la polilla del tomate, *Phthorimaea absoluta* (Meyrick), a insecticidas en Arica. *Agricultura Técnica.* **61**(4):429–435. https://doi.org/10.4067/S0365-28072001000400004

Sanju T, and Saxena SK. 2020. Incidence of leafminer (*Liriomyza trifolii* Burgess) on tomato crop in relation to the climatic conditions of South Gujarat. *Biosci*. **10**(8):1673–1676.

Sankarganesh E, *et al.* 2017. Invasion of the South American Tomato Pinworm, *Phthorimaea absoluta*, in northeastern India: A new challenge and biosecurity concerns. *Entomol*. **36**(4):335–345. https://doi.org/10.1127/entomologia/2017/0489

Sharma PL, and Gavkare O. 2017. New distributional record of invasive pest *Phthorimaea absoluta* (Meyrick) in North-Western Himalayan Region of India. *Natl Acad Sci Lett*. **40**(3):217–220. https://doi.org/10.1007/s40009-016-0526-1

Shashank PR, *et al.* 2016. Report of invasive tomato leafminer, *Phthorimaea absoluta* (Lepidoptera:Gelechiidae) from northern India. *Indian J. Agric. Sci.* **86**(12):1635–1636.

Silva TBM, *et al.* 2016. Susceptibility levels of *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae) to minor classes of insecticides in Brazil. *J. Crop Prot*. **79**:80–86. https://doi.org/10.1016/j.cropro.2015.10.012

Siqueira HAA, *et al.* 2001. Abamectin resistance and synergism in Brazilian populations of *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae). *Int. J. Pest Manag.* **47**(4):247–251. https://doi.org/10.1080/09670870110044634

Siqueira HÁA, Guedes RNC, and Picanço MC. 2000. Insecticide resistance in populations of *Phthorimaea absoluta* (Lepidoptera:Gelechiidae). *Agric. For. Entomol.* **2**(2):147–153. https://doi.org/10.1046/j.1461-9563.2000.00062.x

Sridhar V, Chakravarthy A, and Asokan R. 2014. New record of the invasive South American tomato leafminer, *Phthorimaea absoluta* (Meyrick) (Lepidoptera:Gelechiidae) in India. *Pest Manage. Hortic. Ecsyst*. **20**(2):148–154.

Tabashnik BE, *et al.* 2003. Insect resistance to transgenic Bt crops: Lessons from the laboratory and field. *J. Econ. Entomol.* **96**(4):1031–1038. PMid: 14503572. https://doi.org/10.1093/jee/96.4.1031

Toews MD, Subramanyam B, and Rowan JM. 2003. Knockdown and mortality of adults of eight species of stored-product beetles exposed to four surfaces treated with spinosad. *J. Econ. Entomol.* **96**(6):1967–1973. PMid: 14977140. https://doi.org/10.1093/jee/96.6.1967

Trucksess MW, and Scott PM. 2008. Mycotoxins in botanicals and dried fruits: a review. *Food Addit. Contam*. 25(2):181–192. PMid: 18286408. https://doi.org/10.1080/02652030701567459

Viggiani G, *et al.* 2009. *Phthorimaea absoluta*, a new Lepidoptera now reported in Italy. *Inf. Agrar*. **65**(2):66–68.

Watson GB, *et al.* 2010. A spinosyn-sensitive Drosophila melanogaster nicotinic acetylcholine receptor identified through chemically induced target site resistance, resistance gene identification and heterologous expression. *Insect Mol. Biol.* **40**(5):376–384. PMid: 19944756. https://doi.org/10.1016/j.ibmb.2009.11.004

Weissenberg M, *et al.* 1998. The effect of some Solanum steroidal alkaloids and glycoalkaloids on larvae of the red flour beetle, *Tribolium castaneum*, and the tobacco hornworm, *Manduca sexta*. *Phytochem. Lett.* **47**(2):203–209. https://doi.org/10.1016/S0031-9422(97)00565-7

Zappalà L, *et al.* 2012. Efficacy of sulphur on *Phthorimaea absoluta* and its side effects on the predator Nesidiocoris tenuis. *J. Appl. Entomol.* **136**(6):401–409. https://doi.org/10.1111/j.1439-0418.2011.01662.x

Zappala L, *et al.* 2013. Natural enemies of the South American moth, *Phthorimaea absoluta*, in Europe, North Africa and Middle East and their potential use in pest control strategies. *J. Pest Sci.* **86**(4):635–647. https://doi.org/10.1007/s10340-013-0531-9