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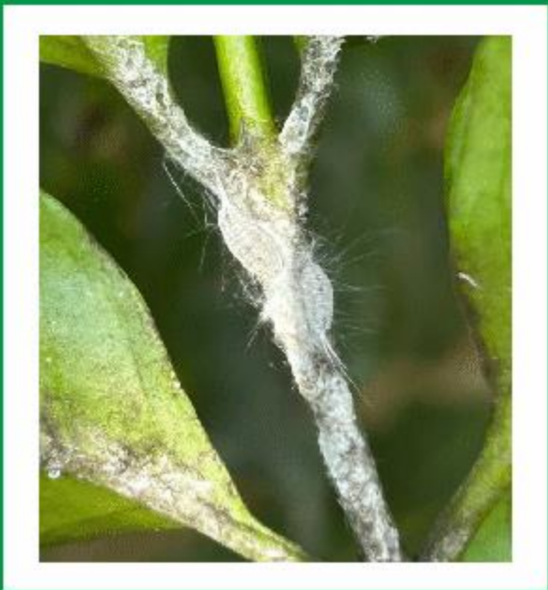

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Contents

Photo of the cover page: Striped mealybug on coffee plant (Courtesy *Bouzid Nasraoui*)

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Guest Editorial

Agrochemical products: Between agricultural necessity and environmental and health issues

Brief history of pesticides

The need to protect crops from pests and diseases is as old as agriculture itself. For instance, the Sumerians used sulfur 4,500 years ago to repel insects and fungi from their fields and storage facilities. In the Roman Empire, various methods were employed, including mosquito nets, elevated silos, sticky traps on trees, and plant-based pesticide extracts. However, ancient practices also included toxic compounds based on arsenic and heavy metals, which were far less environmentally friendly and posed dangers not only to pests but also to humans and ecosystems. It is only in recent decades that corrosive mercury-based seed treatments have been replaced by modern active substances.

Since the discovery of DDT's insecticidal properties in 1935 and its widespread use, pesticides have become indispensable tools for crop protection and for meeting the food demands of a growing global population. Since, numerous chemical families have been synthesized, forming three principal classes: insecticides, fungicides, and herbicides, and more.

However, their intensive and unreasonable use has raised critical concerns regarding their environmental impact, human health risks, and the long-term sustainability of agricultural systems. Indeed, since 1960, the negative effects of pesticides have been highlighted in Racher Carson's book 'The Silent Spring', in which she sounded the alarm about the unwise use of these products and their effects on farmers' health and the decline of non-target populations such as birds.

A pillar of agricultural production

Since the mid-20th century, pesticides have provided significant benefits, particularly to the economy, agriculture, and public health. They have made farmers' work easier, increased yields and eliminated many insect-borne diseases such as malaria. They have also helped to stabilize food supplies, playing a crucial role in global food security. A number of active substances have been shown to be effective in controlling many diseases and limiting the spread of many pests, improving the efficiency of farming practices.

Despite the promising results of this chemical management, its efficiency has often been achieved at the expense of a holistic approach to farm management, leading to monotony in pest management without an intelligent systems approach. Moreover, the excessive or inappropriate use of pesticides has led to many acute and chronic problems such as the emergence of resistance in bio-aggressors and a decline in biodiversity in agricultural ecosystems.

Challenges and consequences

Despite these achievements, the extensive use of chemicals in agriculture, including pesticides, has raised concerns about their long-term effects. Environmental pollution, illustrated by plastic waste, chemical spills and water contamination, underscores the unintended consequences of chemical innovation. Persistent organic pollutants (POPs) including many banned pesticides like DDT and endosulfan, along with hazardous industrial chemicals have been linked to severe environmental and health problems, including bioaccumulation in food chains and chronic diseases in humans.

Furthermore, the production and disposal of chemicals contribute significantly to greenhouse gas emissions, intensifying climate change. The reliance on non-renewable resources for chemical manufacturing has also sparked questions about the sustainability and resilience of the chemical industry in the context of resource scarcity.

The other side of pesticide use

The environmental impact of pesticides has been a growing concern since the 1960s and continues to intensify today. Their persistence in soil, contamination of water resources, and toxicity to non-target organisms, such as pollinators, underscore the urgent need to regulate and limit their use. For instance, the gradual decline in bee populations has been strongly linked to the use of certain systemic insecticides, particularly those belonging the chloronicotinyl chemical family.

From a public health perspective, pesticide residues in food remain a significant concern. While tolerance thresholds are in place, the cumulative effects of long-term exposure are still poorly understood. Furthermore, the consequences of the accumulation of various active substances in the human body - referred to as the "cocktail effect" - have not yet to be fully elucidated, leaving potential health risks inadequately addressed.

Toward sustainable solutions

Faced with this alarming situation linked to a global imbalance, the chemical industry is at a crossroads, with an urgent need to transition towards more sustainable practices. The principles of green chemistry, which focus on designing products and processes that minimize environmental and health impacts, offer a promising way forward. Innovations in bio-based chemicals, biodegradable materials and energy-efficient production methods are helping to reduce the ecological footprint of chemicals.

In addition to these industrial innovations, regulations and international agreements, such as the Stockholm Convention on POPs, are supporting a growing awareness of the need to reduce the use of harmful substances. Collaboration between governments, industry and research institutions is essential to encourage the development and adoption of safer and more sustainable chemical/biological solutions.

Toward a new generation of pesticides

In response to these challenges, crop protection research is increasingly focusing on more sustainable alternatives. Biopesticides, derived from natural organisms, and plant defense stimulators are promising avenues. These solutions reduce the impact on the environment while maintaining the effectiveness of pest control.

In addition, technological advances such as precision spraying, the use of drones, the microencapsulation of pesticides and analysis tools based on data and damage localization enable *better dose management and targeted application, thus reducing waste and side-effects.*

Conclusion

Since their invention, pesticides have played a central role in the development and growth of modern agriculture. However, their intensive use has had environmental, health and social consequences. The future of crop protection lies in a transition towards integrated and systemic approaches, combining biological, cultural, technological and ultimately chemical solutions. By adopting a more sustainable vision, it is possible to reconcile agricultural production and preservation of the environment, while meeting society's expectations for responsible, resilient agriculture.

Prof. Hanène Chaabane-Boujnah
INAT, University of Carthage, Tunis
Tunisia

Tribute to the late Prof. Abderrahmane Jerraya
(14/10/1940 - 1/8/2024)

The eminent entomologist ecologist: A life in the service of plant protection

Last September 28th, 2024 was commemorated at the National Agronomic Institute of Tunisia (INAT) the 40th day after the death of Professor Emeritus Abderrahmane Jerraya, one of the greatest teachers in this prestigious institute and one of the initiators of ecological awareness for many generations.

Prof. A. Jerraya hold a diploma in agricultural engineering from ENSAT (Ecole Nationale Supérieure d'Agriculture de Tunis) in 1965, followed by a DEA in Animal Biology (Faculty of Sciences of Paris) in 1967, then a Doctorate third cycle (Faculty of des Sciences of Paris VI) in 1969, and finally a PhD in Biological Sciences from the University of Paris VI-Pierre et Marie Curie, in 1975.

Prof. A. Jerraya began his career as a teacher-researcher in entomology in 1972. He taught entomology, zoology, ecology, population biology, phytopharmacy and parasitology in several higher education institutions, in particular at INAT where he was affiliated (1972-2002). All his students, and myself in particular, can testify to his exceptional teaching, driven by a communicative passion for insects. Prof. A. Jerraya was very eloquent, in describing insects in minute detail, even miming them... which never failed to arouse the curiosity of students for the extraordinary world of insects. Prof. A. Jerraya also taught us the basics of ecology and the preservation of natural resources and human health, always striving to reduce the use of pesticides *and promoting integrated pest management and sustainable methods.*

In the 1970s, Prof. A. Jerraya founded the entomology and ecology laboratory at INAT. In collaboration with his team, Prof.A. Jerraya was able to conduct a wide range of research on crop pests, in particular on insects of stored foodstuffs, pistachio, olive, date palm, citrus and stone trees. Prof. A. Jerraya's observations were carried out in close connection with field problems, aiming to provide farmers with applicable solutions. Prof. A. Jerraya's work has always been based on a sound knowledge of pest species in their environment, and on analysis of the ecological factors regulating their populations (life cycle, susceptible stages, population dynamics, regulatory factors, cultivation practices, etc.) in order to design control strategies that reduce the use of insecticides, while ensuring satisfactory crop protection.

Prof. A. Jerraya supervised more than fifteen student projects, final year projects and theses at INAT and other universities. His students, including myself, remember him as a passionate and perfectionist supervisor who imparted on not only immense knowledge, but also the values of intellectual honesty, ethics and rigor.

The results of Prof. A. Jerraya's research made a major contribution to the progress of plant protection and agricultural development in general, by proposing innovative pest management programs, always with a view to preserving nature and humanity. Prof. A. Jerraya has authored over thirty publications in national and international journals, as well as book chapters, and he has contributed to or carried out many studies on various topics. These include studies on the promotion of integrated pest management, biodiversity in Tunisia and the development of a strategy on the use and storage of pesticides in natural and agricultural environments, commissioned by the Ministry of the Environment. Prof A. Jerraya was committed to raising public awareness of important causes, and has also written several articles for the press.

Prof. A. Jerraya's expertise in entomology, and environment and sustainable development has been recognized internationally, and resulted to his invitation to give specialized courses in France (1980s-90s), or as a member of the International Organization for Biological Control (IOBC) (1985-1993) or a member of the Ahmed El Fasi Jury for research in agronomy and plant production (1993-1996 and 1999). At the national level, Prof. A. Jerraya was appointed as advisor to the Minister of Agriculture, Hydraulic Resources and Fisheries from 1991 to 2000.

During the period 1981-1989, Prof. A. Jerraya was the General Director of INAT. During his tenure, he distinguished himself by his seriousness, his sound management of educational and administrative affairs, and his constant concern to make INAT an institute of excellence in tune with the times, and a provider of future executives for the agricultural sector. It was notably during Prof. A. Jerraya's tenure that the specialization cycle and the PhD in Agronomic Sciences were created.

After his retirement in 2002, Prof. A. Jerraya devoted himself to associative activities, working for integrated, equitable and sustainable rural development.

Among his works, Prof. A. Jerraya co-authored and coordinated a book[1] *that was produced on the occasion of INAT's centenary. This event, organized by Prof. A. Jerraya as team leader, was celebrated in 1998, with the participation of many prestigious guests and school alumni from various countries. A second book*[2]*, on insect pests of main crops in North Africa and their management, was also written by Prof. A. Jerraya and published in 2003. For anyone interested, this latter, together with Prof. A. Jerraya's scientific publications, are available at INAT's entomology and ecology laboratory.*

I would like to pay tribute to my dear great professor, who is an exceptional role model for me and for the generations that have known him, for his uprightness, his commitment to effort and progress, and for so many other values that he passed on to us.

May his soul rest in peace.

[1] : L'INAT, un siècle sur la voie de l'excellence, 1998. Association des Anciens de l'INAT, Tunis, Tunisie, 568 pp.

[2] : Principaux nuisibles des plantes cultivées et des denrées stockées en Afrique du Nord (leur biologie, leurs ennemis naturels, leurs dégâts et leur contrôle), 2003. Edition Climat Pub, Tunisie, 415 pp.

***Prof. Synda Boulahia Kheder* (*synda.kb@gmail.com*),**
Professor of Entomology and Ecology at INAT, University of Carthage, Tunis,
Former student and assistant (1988-2006) of the late Prof. A. Jerraya,
Tunisia

Short Communication

New Record of *Leptadenia arborea* (Forssk.) Schweinf. in the Flora of Libya

Sh-Hoob M. El-Ahamir, Botany Department, Faculty of Science, Gharyan University, Gharyan, Libya**, and Khaleefah S. Imohammed,** Botany Department, Faculty of Science, Sabha University, Sabha, Libya

https://dx.doi.org/10.4314/tjpp.v19i2.1 (*Libya*)

ABSTRACT

El-Ahamir, S.M. and Imohammed, K.S. 2024. New record of *Leptadenia arborea* (Forssk.) Schweinf. in the flora of Libya. Tunisian Journal of Plant Protection 19 (2): 63-68.

A new record for *Leptadenia arborea* (Forssk.) Schweinf. is reported for the first time in the flora of Libya. This species was collected from Ariggiba region (110 km southwest Sabha city). A full description and habitat information on the plant are provided. A brief discussion about the most important traits of this species is presented.

Keywords: *Leptadenia arborea*, Libya, Sabha**,** tree of life

Leptadenia arborea (Forssk.) Schweinf. commonly known as the tree of life, is a climbing shrub from the Apocynaceae family. Its distribution extends across diverse habitats in these regions, demonstrating its adaptability to various environmental conditions. This fact can be attributed to several factors: (i) a remarkable ability to adapt to harsh climatic conditions and (ii) seeds are likely dispersed by wind and water (Batanouny and El-Sheikh 2003).

In North Africa, the introduction of *L. arborea* may have occurred through human activities. The plant is valued for its medicinal properties and its role in traditional practices (treat syphilis, migraine, and mental illnesses), which could have led to its intentional cultivation in gardens and agricultural systems (Sharma et al. 2012). Additionally, the expansion of trade routes and agricultural practices may have facilitated its unintentional spread.

In Libya, only *Leptadenia pyrotechnica* (Forsk.) Decne was reported from Wadi Tafilamin, Ghat, Ghadames and Marzuk (Ali and Jafri 1977, Jafri and El-Gadi 1989) belonging to Asclepiadaceae family. This study reports a new record of *L. arborea* (Forssk.) Schweinf. in Libya.

MATERIALS AND METHODS

Specimens of *L. arborea* were found, photographed, collected and identified as a result of field surveys (2023-2024), from several localities of Sabha and from Ariggiba Region, 110 km

Corresponding author: Sh-Hoob M. El-Ahamir
Email: Shhoob.Elhmir@gu.edu.ly

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southwest Sabha city about 1000 km south of Tripoli, (26˚ 58’ 63.6" N , 13˚ 49’ 03.4" E) (Fig.1). Plants were identified as *L. arborea*, the voucher specimens were deposited in the herbarium of Botany Department, Faculty of Science, University of Sabha using the data from several references (Ahmed et al. 2009, Boulos 2000, Darbyshire et al. 2015, Davis 1970, El-Sheikh et al. 2014, Hedberg et al. 2003, Thulin 2006). The plant species was given voucher number (02912N). The Voucher specimens were deposited in the same herbarium, with a duplicate sent to the herbarium of the Botany Department, Gharyan University, Gharyan, Libya (Fig.2).

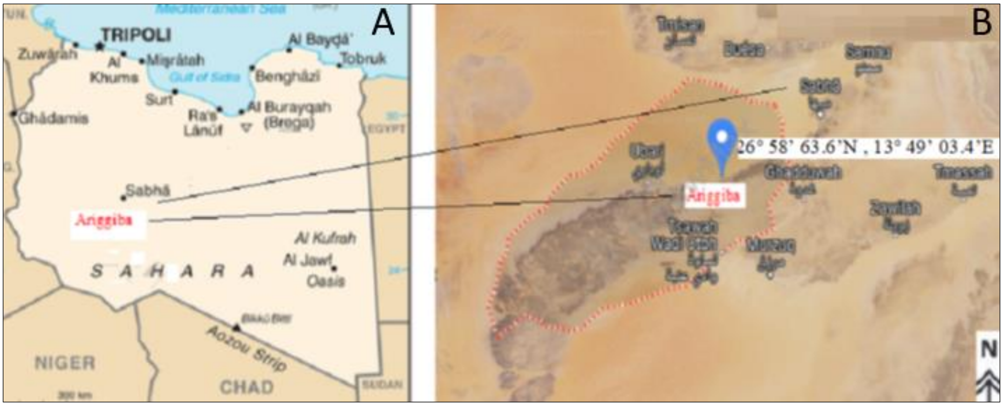

Fig 1. Map of Libya (A) and detailed map of the Sabha district (B) showing the locality where *Leptadenia arborea* was collected.

RESULTS AND DISCUSSION

Accepted name: *Leptadenia arborea* (Forssk.) Schweinf.

Homotypic synonyms: *Cynanchum arboretum* Forssk.

Heterotypic synonyms: *Leptadenia abyssinica* Decne, *Leptadenia clavipes* S. Moore, *Leptadenia delilei* Decne, *Leptadenia forskalii* G. Don, *Leptadenia jazanica* Masrahi.

English common name: Tree of life.

Plant description.

Leptadenia arborea typically grows up to 3 m tall. Its biological features are slender, erect stems with a smooth or slightly rough texture. The leaves are arranged oppositely, generally linear to lanceolate, measuring 5-15 cm in length and 1-3 cm in width. They are green, with a glabrous surface that helps reduce water loss (Batanouny and El-Sheikh 2003). The flowers are small, tubular, and usually white to yellow, with a pleasant fragrance (Fig. 2). They are borne in clusters, attracting various pollinators. The fruit is a slender, elongated follicle that contains several seeds, which are dispersed by wind or water (Abdel-Hamid et al. 2016). Its chromosome number is reported to be 2n = 22. This diploid number is consistent with various studies on the genetic characteristics of the species (Batanouny and El-Sheikh 2003, El-Sheikh and Batanouny 2007).

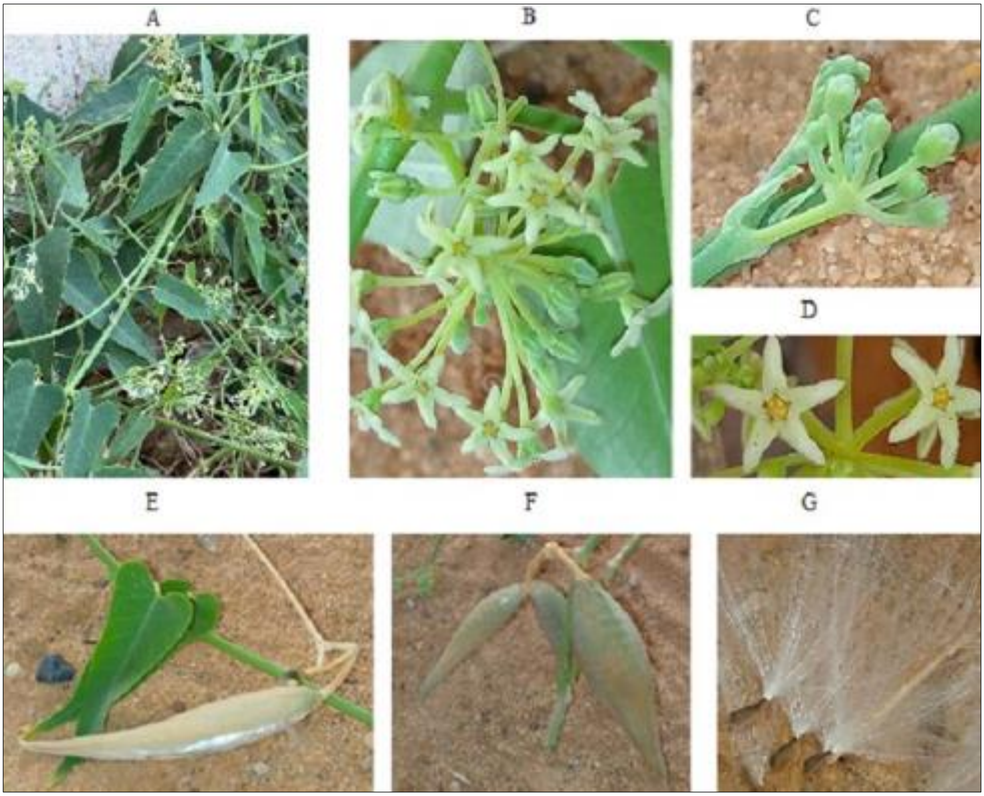

Fig 2. *Leptadenia arborea*. A: Habit, B: Inflorescence, C: Flower buds, D: flowers, E: leaves, F: follicle, G: seeds.

Distribution.

According to "African Plant Database", "efloramaghreb", "Plants of the World Online", "World Flora Online", *L. arborea* is found in Algeria, Burkina, Cameroon, Central African Republic, Chad, Djibouti, Egypt, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Somalia, Sudan, and Yemen.

Habitat.

L. arborea thrives in a variety of habitats, predominantly dry, sandy, and rocky soils. It is commonly found in open woodlands, scrublands, and along riverbanks, where it can access moisture during the rainy season (El-Sheikh et al. 2014). It is well-adapted to withstand drought conditions. Its deep root system allows it to access groundwater, enabling it to survive in challenging environments (Abdel-Hamid et al. 2016).

L. arborea is a perennial shrub or small tree native to the arid regions of Africa and the Arabian Peninsula, particularly found in countries such as Sudan and Egypt. Its adaptability allows it to thrive in diverse habitats, including open woodlands and scrublands. In Libya, the genus *Leptadenia* is represented by only one species, as documented in the flora of Libya (Ali and Jafri 1977, Keith 1965, Jafri and El-Gadi 1989). This study marks the first record of *L. arborea* in the

Sabah and Ariggiba regions of Libya, increasing the number of *Leptadenia* species in the country to two.

Overall, the successful introduction and establishment of *L. arborea* in Libya highlight its adaptability to local ecological conditions, making it a significant addition to the region's flora. Continued research is essential to further understand its ecological role and potential conservation implications within North African ecosystems.

Distribution in Libya.

Plants of *L. arborea* were found near dried water bodies and wastelands of Ariggiba region (26˚ 58' 63.6" N, 13˚ 49' 03.4" E) located approximately 110 km Southwest of Sabha region of Libya, about 1000 km south of Tripoli. In addition, plants have been detected in several regions of Sabha (26° 41' 37.3" N 13° 48' 55.2" E to 27˚ 04' 00.46" N, 14˚ 43' 35.61" E) (Fig. 3).

This finding is significant as of *L. arborea* was not previously documented in the flora of Libya compiled by Jafri and El-Gad (1989) and Keith (1965), indicating that this represents a new addition to the plant species diversity of the country.

Fig 3. Herbarium specimen of *Leptadenia arborea* (Forssk.) Schweinf. collected from Ariggiba region, Sabha, Libya.

Key to the genus *Leptadenia* in the flora of Libya.

Since the key of the genus *Leptadenia* mentioned in the flora of Libya includes only one species, this study provides a classification key that includes *L. pyrotechnica* and *L. arborea*.

1.(a) Leaves opposite, stipulate, asymmetrical at base. Plants small, prostrate …….……. **2(a)**

(b) Often a shrub or small tree, reaching heights of up to 3 m ……………………….. **2(b)**

2.(a) Slender, upright stems and narrow leaves. Small and fragrant flowers, white or yellow……………………………………………………………………... ***L. pyrotechnica***

(b) Broader leaves compared to *L. pyrotechnica*, often with a more robust appearance. Flowers clustered, with a similar color range…………………………..……..… ***L. arborea***

The classification of *L. arborea* has evolved significantly, driven by advancements in phylogenetic studies and a deeper understanding of plant relationships. Initially classified within the Asclepiadaceae family, it was later reclassified into the Apocynaceae family based on genetic and morphological evidence. Molecular studies utilizing DNA sequencing demonstrated that many genera once categorized under Asclepiadaceae are more closely related to those in Apocynaceae, prompting a reevaluation of family boundaries (Endress and Igersheim 2000).

Moreover, both families share certain morphological traits, particularly in the structure of their flowers and fruits. However, specific characteristics of *L. arborea* align more closely with those of the Apocynaceae family, leading taxonomists to reassess its classification. The integration of molecular data into taxonomic frameworks has resulted in significant reclassifications, with many species, including *L. arborea*, being reassigned to Apocynaceae in light of their phylogenetic relationships (APG III 2009).

CONCLUSION

This study highlights the expanding global distribution of *L. arborea*, a species native in the Sahara, Sahel, and Arabian Peninsula. The findings show its ability to naturalize and establish populations outside its native range, including its first recorded presence in Libya's flora. The spread of *L. arborea* in Libya and other parts of North Africa can be attributed to unintentional dispersal, intentional introduction, and its adaptability to regional environmental conditions.

RESUME

El-Ahamir S.M. et Imohammed K.S. 2024. Nouvelle observation de *Leptadenia arborea* (Forssk.) Schweinf. dans la flore de la Libye. Tunisian Journal of Plant Protection 19 (2): 63-68.

Une nouvelle observation de *Leptadenia arborea* (Forssk.) Schweinf. est enregistrée pour la première fois dans la flore de la Libye. Cette espèce a été collectée dans la région d'Ariggiba (110 km au sud-ouest de la ville de Sabha). Une description complète et des informations sur l'habitat sont fournies. Une brève discussion sur les traits les plus importants de cette espèce est présentée.

Keywords: arbre de la vie, *Leptadenia arborea*, Sabha

ملخص

الأحمر، شهوب م. وخليفة س. إمحمد. 2024. تسجيل جديد لنبات *Leptadenia arborea* (Forssk.) Schweinf. في فلورة ليبيا. Tunisian Journal of Plant Protection 19 (2): 63-68.

تم تسجيل نوع نبات جديد هو *Leptadenia arborea* (Forssk.) Schweinf. لأول مرة في فلورة ليبيا. تم جمع هذا النبات البري المنتشر في منطقة الرجيبا (110 كم جنوب غرب مدينة سبها). تم تشخيص ووصف النبات وتقديم معلومات وبيانات حول توزّعه وانتشاره. وتمت تقديم مناقشة موجزة حول أهم السمات التي يتّسم هذا النوع النباتي.

كلمات مفتاحية: سبها، شجرة الحياة، *Leptadenia arborea*

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Arabica Coffee Arthropod Pests and Their Management in Ethiopia: Current Status and Future Prospective

Tamiru Shimales, and Desalegn Alemayehu, Jimma Agricultural Research Center, Ethiopian Institute of Agricultural Research, P.O. Box 192, Jimma, Ethiopia
https://dx.doi.org/10.4314/tjpp.v19i2.2 (*Ethiopia*)

ABSTRACT

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Arabica coffee (*Coffea arabica*) is one of the most important commodities that is cultivated in various agro-ecologies of Ethiopia. The perennial and evergreen nature of the coffee favors attack by several insects, diseases, mites, and some gastropods such as snails and slugs. All parts of the plants are susceptible to be attacked, and damage could appear at different crop growth stages. Coffee insects damage seedling, reduce coffee yield and quality. Many insects found in coffee agroforestry system are not pests; many are even beneficial as they feed upon the coffee pest species. Worldwide over 3000 insects and mites are associated with coffee. In Ethiopia, more than 59 arthropod pests have been identified and documented in coffee from 1966 till the present. From identified arabica coffee arthropods in the country around 30.51% are Hemiptera order whereas 28.81% are Lepidoptera order. Glasshouse orthezia (*Insignorthezia insignis*), mealybugs (*Planococcus* spp. and *Pseudococcus* spp.) and greenhouse whiteflies (*Trialeurodes* spp.) are the pest currently recorded in Ethiopia. Besides, due to changing farm dynamics from time to time and current climate change, some previously uncommon pests are appearing and discussed in this review. Coffee insect pests are more problematic in coffee plantation system. Pesticide-free pest management options under changing climatic conditions are crucial. As future prospective, it is very important to conserve natural enemies through the diversification in the coffee farms. In future, identifying the impacts of climate change on coffee associated insect species, and mass rearing and release of natural control agents could allow for the sustainable production in Ethiopia. Therefore, this review presents the past, current status of coffee arthropod pests and their management options in Ethiopia.

Keywords: Arabica coffee, arthropod pests, cropping systems, Ethiopia, pest management

INTRODUCTION

Arabica coffee (*Coffea arabica*) is the most important commodity and has been growing in various agro-ecologies of Ethiopia as it is an indigenous crop to the country. Arabica coffee is under attack by several insects, diseases, mites, and some gastropods such as snails and slugs. All portions of the plants (root, stem, branch, leaf, flower and fruit) are susceptible to many coffee pests at different crop growth stages. Over 3000 species of insects and mites are associated with coffee worldwide (Waller et al. 2007). In Ethiopia over 46 coffee insect

Corresponding author: Desalegn Alemayehu
Email: alemayehu16@yahoo.com

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species and 3 coffee mites were reported (Abedeta et al. 2015; Abebe 1987; Mendesil et al. 2008). Recently, insects such as mealybugs (*Planococcus* spp. and *Pseudococcus* spp.), greenhouse whiteflies (*Trialeurodes* spp.) and glasshouse orthezia (*Insignorthezia insignis*) are the pests currently recorded in coffee (Shimales 2019; JARC 2023/24; Shimales 2023). Till today, the coffee insect pests infesting coffee in Ethiopia are increased to over 59 insect pests (Table 1).

Different agro-ecologies (low to high altitude), coffee production types (forest-unmanaged wild to plantation, modern farming system), varied shade types and various coffee genotypes found in Ethiopia are opportunities for successful development of integrated coffee pest management strategies. Pests reached outbreaks and are more problematic in the most intensively managed coffee production system than in the forest coffee production system (Asfaw et al. 2019; Burger et al. 2021; Shimales et al. 2023a). This might be due to management practices (pesticide use) that could have impact on biological control, which is the suppression of pest level by natural enemies without human intervention (Diehl et al. 2013; Martin et al. 2013) and also beneficial insects like parasitoids and predators are often more abundant in less managed systems than in intensive farming systems (Medeiros et al. 2019). In addition, the genetic uniformity of coffee cultivars planted in intensive farming may favor the adaptation of insects to the crop (Shimales et al. 2023a). Besides, the study indicated parasitism rate of insect pests was lower, and the parasitoid community was distinct, in absolute managed coffee production systems (Medeiros et al. 2019; Shimales et al. 2023a). The objective of this paper is to discuss the past, current status of coffee arthropod pests recorded in Ethiopia and their management options.

ARABICA COFFEE ARTHROPOD PESTS

In Ethiopia over 56 coffee insect pests and 3 mite pests associated with arabica coffee were documented since 1966 to 2024. In addition to arthropod pests, gastropods (snails and slugs) become serious problem in Gomma district of Jimma zone (Shimales 2019). From identified arabica coffee arthropods in the country, around 30.51% are Hemiptera order (including bugs and scale insects) and followed by Lepidoptera (28.81%) (Table 1). Based on the part of the plant they attack, coffee insect pests are grouped in to berry-feeding insects, stem borers and branch borers, insects that feed on buds, leaves, green shoots and flowers, and root and collar-feeding insects (Waller et al. 2007). Based on the damage they cause to the coffee parts over 59 arabica coffee arthropod pests were indicated in the Table 1.

Leaf feeding insect pests.

Until 2015 a total of 49 coffee insect species reported in Ethiopia (Abdeta et al. 2015; Abebe 1987; Mendesil et al. 2008). Among these pests, coffee blotch miner (*Leucoptera caffeina*) and antestia bugs (*Antestiopsis intricata* and *A. facetoides)* were identified as major coffee insect pests in the country (Abebe and Murmane 1986; Abebe 1987, 2000). However, due to current climate change and change of farming practices, the status of minor insect such as coffee thrips, coffee berry moth, scale insects and stem borers has been increasing (Shimales 2019). Different scholars reported that different parts of coffee are attacked by various insect pests. The leaf damaging insect pests are coffee blotch miner, coffee leaf skeletonize, serpentine leaf miner and other free feeding herbivory damage have been assessed in southwestern Ethiopia (Abdeta et al. 2015; Beche et al. 2023;

Mendesil, 2019; Shimales and Beksisa, 2021; Shimales et al. 2017; Shimales 2019, Shimales et al. 2023a; Samnegard et al. 2014). However, the infestation level of these insect pests in the country varied due to difference in management gradients, shade level, farming practices, altitudinal gradients and seasons. Biology of some insect pests, classification of pests based on plant parts damaged and their management practices were reviewed by Mendesil (2019). However, coffee pests and their management although reviewed at various times by different researchers in the country. Nevertheless, due to the current weather variables and changing farm dynamics from time to time, some previously uncommon pests are appearing and affecting coffee yield and quality. It is important to take into account such compiled information to identify pests and moving towards pesticide free pest management strategies.

Table 1. Arabica coffee arthropod pests in Ethiopia

Common name	Scientific name	Order and family
Berry/fruit/ feeding pests		
Coffee berry moth	*Prophantis smaragdina*	Lepidoptera: Pyralidae
Coffee berry borer	*Hypothenemus hampei*	Coleoptera: Curculionidae
Berry worm	*Cryptophlebia batrachopa*	Lepidoptera: Tortricidae
Berry butterfly	*Deudorix lorisona*	Lepidoptera: Lycaenidae
Natal fruit fly	*Ceratitis rosa*	Diptera: Tephritidae
Mediterranean fruit fly	*Ceratitis capitata*	Diptera: Tephritidae
Fruit fly	*Ceratitis fasciventris*	Diptera: Tephritidae
Fruit fly	*Ceratitis anonae*	Diptera: Tephritidae
Antestia bug	*Antestiopsis intricata*	Hemiptera: Pentatomidae
Antestia bug	*Antestiopsis orbitalis*	Hemiptera: Pentatomidae
Antestia bug	*A. thunbergii ghesquierei*	Hemiptera: Pentatomidae
Antestia bug	*Antestiopsis facetoides*	Hemiptera: Pentatomidae
Soap berry bug	*Leptocoris affinis*	Hemiptera: Rhopalidae
Stem feeder pests		
White coffee stem borer	*Monochamus leuconotus*	Coleoptera: Cerambycidae
Black borer	*Apate monachus*	Coleoptera: Bostrichidae
Black borer	*Apate indistincta*	Coleoptera: Bostrichidae
Asian ambrosia beetle	*Xyleborus xanthopus*	Coleoptera: Scolytidae
Cocoa stem borer	*Eulophonotus myrmeleon*	Lepidoptera: Cossidae
Branch borer	*Ethmia iphicartes*	Lepidoptera: Ethmiidae
Cossid stem borer	*Duomitus* sp.	Lepidoptera: Cossidae

Coffee leaf feeding pests		
Coffee blotch miner	*Leucoptera meyricki*	Lepidoptera: Lyonetiidae
Coffee blotch miner	*Leucoptera caffeina*	Lepidoptera: Lyonetiidae
Serpentine leaf miner	*Cryphiomystis aletreuta*	Lepidoptera: Gracillaridae
Coffee leaf skeletonizer	*Leucoplema dohertyi*	Lepidoptera: Epiplemidae
Giant looper	*Ascotis selenaria reciprocaria*	Lepidoptera: Geometridae
Green tortrix	*Archips occidentalis*	Lepidoptera: Tortricidae
Brown tortrix	*Tortrix dinota*.	Lepidoptera: Tortricidae
Branch, stem, leaf and berry feeding pests		
Green scale	*Coccus alpinus*	Hemiptera: Coccidae
Coffee bark scale	*Avricus arborescens*	Hemiptera: Coccidae
White waxy scale	*Ceroplastes brevicauda*	Hemiptera: Coccidae
Halmet scale	*Saissetia coffeae*	Hemiptera: Coccidae
Citrus mussel scale	*Lepidosaphes beckii*	Hemiptera: Diaspididae
Rufous scale	*Selenaspidus articulatus*	Hemiptera: Diaspididae
Black thread scale	*Ischnaspis longirostris*	Hemiptera: Diaspididae
Coffee cushion scale	*Stictococcus formicarius*	Hemiptera: Stictococcidae
Coffee aphid	*Toxoptera aurantii*	Hemiptera: Aphididae
Coffee thrips	*Diarthrothrips coffeae*	Thysanoptera: Aeolothripidae
Coffee thrips	*Selenothrips rubrocinctus*	Thysanoptera: Aeolothripidae
Cutworm	*Agrotis* sp.	Lepidoptera: Noctuidae
Cutworms	*Euxoa* spp.	Lepidoptera: Noctuidae
Chafer grubs	*Phyllophaga* spp.	Coleoptera: Scarabaeidae
Stinging caterpillar	*Parasa vivida*	Lepidoptera: Cochlidiidae
Systates weevil	*Systates* sp.	Coleoptera: Curculionidae
Lamiine	*Sophronica* sp.	Coleoptera: Cerambycidae
Coffee leaf fly	*Tropicomyia flacourtiae*	Diptera: Agromyzidae
Coffee lygus	*Lygus coffeae*	Heteroptera: Miridae
Coffee capsid	*Lamprocapsidea coffeae*	Heteroptera: Miridae
Dusty brown beetle	*Gonocephalum simplex*	Coleoptera: Tenebrionidae
African silk worm	*Anaphe panda*	Lepidoptera: Notodontidae
*Red crevice mite	*Brevipalpus* sp.	Acari: Tenuipalpidae
*Coffee bronze mite	*Diptilomiopus* sp.	Acari: Diptilomiopidae
*Red coffee mite	*Oligonychus coffeae*	Acari: Tetranychidae
Mealybugs	*Planococcus* spp.	Hemiptera: Pseudococcidae
Mealybugs	*Pseudococcus* spp.	Hemiptera: Pseudococcidae

Greenhouse whiteflies	*Trialeurodes* spp.	Hemiptera: Aleyrodidae
Biting ant	*Tetramorium aculeatum*	Hymenoptera: Formicidae
Weaver ant	*Oecophylla longinoda*	Hymenoptera: Formicidae
Termite	*Coptotermes*	Isoptera: Termitidae
Lantana bug	*Insignorthezia insignis*	Hemiptera: Ortheziidae

* Sources: Abedeta et al. 2015; Abebe 1987; Crowe and Gebremedhin 1984; Greathead 1968; JARC, 2023; Mendesil et al. 2008; Mendesil, 2019; Shimales 2019, 2023.

Coffee blotch miner *Leucoptera caffeina*.

In Ethiopia, two species of coffee blotch miner are documented: *Leucoptera caffeina* and *Leucoptera meyricki* (Abebe 1987; Abebe and Murmane 1986; Crowe and Gebremedhin 1984). The coffee blotch miner *L. caffeina* oviposit its eggs in rows of 1 to 13 eggs (Notley 1956). However, at field conditions up to 17 eggs (1 to 17 eggs in rows) were recorded at Gomma district of Jimma zone (Personal observation). When the larvae hatch, it feeds inside a leaf just below the upper epidermis, resulting in leaf damage (Crowe and Tadesse 1984, Shimales 2019). Pupation occurs either on the tree or fallen leaf (Crowe and Tadesse 1984; Shimales 2019). According to Crowe and Tadesse (1984) the larval, pupa and adult stages for coffee blotch miner were 20-34 days, 7-14 days, and 14 days (for the female), respectively.

L. caffeina is the most economically important species, attacking coffee leaves in nursery and field conditions (Shimale et al. 2017). The larvae create a distinct blotch mine while feeding gregariously in the upper side of the leaf (Notley 1956, Crowe and Tadesse 1984, Shimales et al. 2023a). Mined leaves by coffee blotch miner become dried and fall, as a result yield and life span of coffee tree could be reduced (Shimales and Beksisa 2021). The coffee blotch miner infestation was studied by various authors in different production systems and seasons (Samnegard et al. 2014, Abdeta et al. 2015; Beche et al. 2023; Shimales et al. 2023a).

Coffee thrips (*Diarthrothrips coffeae*).

Coffee thrips is one of the important coffee insect pests found in Ethiopia. Over 42 phytophagous species in 24 genera were associated with coffee flowers in coffee plantations in Chiapas, Mexico (Infante 2017). However, only two species of coffee thrips, namely *Diarthrothrips coffeae* and *Selenothrips rubrocinctus* were documented in Ethiopia (Mendesil et al. 2008). Level of coffee thrips infestation varies and depends on the production type, shade level, altitude and farming system (Shimales et al. 2023b). The estimated infestation of coffee thrips from southern Ethiopia was ranged from 5 to 50% (Guteta et al. 2017). However, it was ranged from very low to very high infestation (0.04 to 100%) in southwestern Ethiopia (Shimales and Alemayehu 2018). Coffee thrips attack the leaves, shoots, nodes, and green berries, and finally defoliates the coffee leaf in severe infestations (Shimales and Beksisa 2021; Shimales et al. 2023b). The pest can cause up to 100% loss during prolonged drought in sun coffee farming system (Shimales and Alemayehu 2018).

Farming practices had strong impact on coffee thrips population density and damage level. The maximum severity of coffee thrips and population was recorded in full-sun system as compared to shaded farm especially under *Albizia schimperiana* plants (Shimales et al. 2023b). Close spacing in full-sun system resulted in higher coffee thrips populations and damage levels (Fig. 1). This indicted that management practices could have impact on pest population either by enhancing the pest or by reducing their generation span. Different cultural practices like shade tree regulation, moisture conservation and plant diversification (intercropping), could manage coffee thrips population below economic threshold level (Fig. 1).

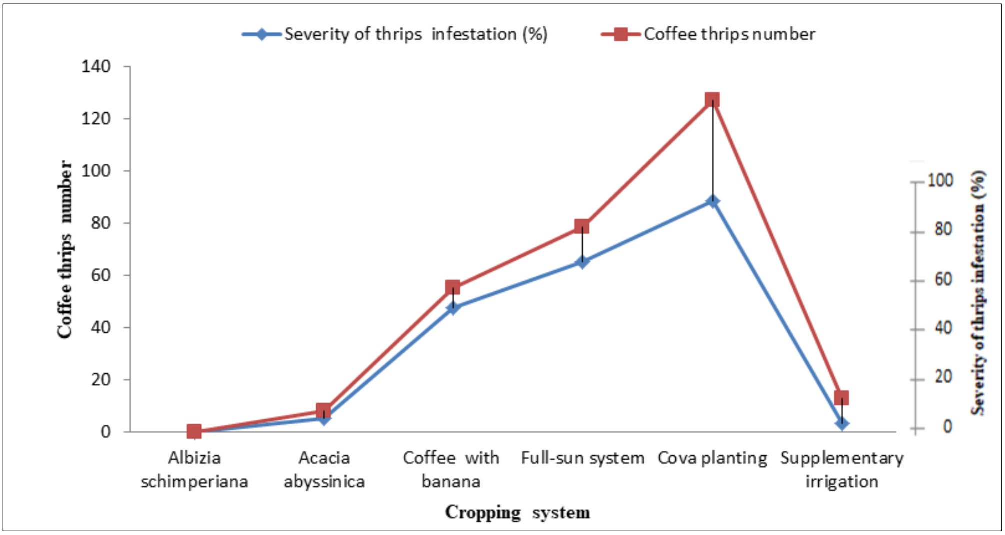

Fig. 1. Coffee thrips density in different farming systems.

Scale insects.

The scale insects feed on buds, leaves, collars, green shoots, flowers and green berries of coffee plant. Till 2000, only 7 scale insect species were documented and identified in Ethiopia (Mendesil et al. 2008). Nowadays, around 13 scale insect species (both armored and soft boded scale insects) were identified and documented. Out of those species of scale insects recorded in Ethiopia coffee, cushion scale (*Stictococcus formicarius*), white waxy scale (*Ceroplastes brevicauda*), and green scale (*Coccus alpinus*) are potentially important pests (Mendesil et al. 2008). Cushion scale is more important in Welega, Metu, and Mugi areas, while the green scale is common in many parts of western Hararghe causing the death of bearing branches (Abebe 1987; 2000). In addition to mealybugs and whiteflies, greenhouse orthezia (*Insignorthezia insignis*) is the scale insect recently (2024) observed in coffee in Ethiopia.

White waxy scale and helmet scale (*Saisettia coffeae*) (Fig. 2) are common in Jimma and Illubabor zones, which cause up to 100% damage level on bearing branches, nodes, leaves and fruits (Shimales 2023). Besides, white waxy scale infests *Acacia abyssinica* and *Sasbania sesban* shade trees in Jimma areas (Shimales 2023).

Fig. **2.** White waxy scale on coffee stem (A), Red one underneath the wax, photographed under microscope (B), and Helmet scale (C).

Mealybugs (*Planococcus* spp. and *Pseudococcus* spp.).

Over 50 species of scales and mealybugs which attack various parts of the coffee tree in different coffee-producing countries are reported (Kumar et al. 2016). However, mealybugs and whiteflies are the pests currently reported in Ethiopia (Shimales, 2019; JARC 2022/23). Various species of *Planococcus* and *Pseudococcus* were recorded in Gera, Mettu and Bebeka areas (Fig. 3). Mealybugs bugs were the most serious pest at Bebeka and Mettu areas. However, long-tailed mealybugs were common at Jimma, Mettu and Gera areas causing the death of bearing branches and green berries.

Fig. 3. Coffee mealybugs. A & B: Adult tailed mealybug (*Ferrisia virgata*), C: Mealybug crawlers of *Pseudococcus* sp.

Berry feeding insects.

Many scholars reported that coffee is attacked by various coffee berry feeding insect such as coffee berry moth (Abdeta et al. 2011; JARC, 2023/24; Mendesil and Tesfaye 2009; Shimales 2019; Shimales et al. 2024), coffee berry borer (Abdeta et al., 2011; EARO 2000; Eyasu 2019; Mendesil et al. 2004; 2008; Shimales et al. 2019), coffee fruit flies (Abedeta et al. 2011; Samnegard et al. 2014; Shimales 2019), and Antestia bugs (Abate et al. 2018;; Chichaybelu 2008; Mendesil et al. 2008, 2019; Shimales 2019; Shimales and Beksisa 2021; Shimales et al. 2017a; Shimales et al. 2023b; Tadesse et al. 1993) in southwest Ethiopia. Among berry-feeding insects, the biology and management of coffee berry borer, Antestia bug and coffee berry moth were reviewed by Mendesil (2019).

Antestia bugs *Antestiopsis* spp.

Among 4 species of Antestia bugs reported in Ethiopia, *Antestiopsis intricata* and *Antestiopsis facetoides* are economically important insect pests (Greathead, 1966; Crowe and Gebremedhin, 1984; and Abebe, 1987). *A. intricata* is the most common bug found in all coffee growing areas of Ethiopia, except at Hararge coffee growing areas. However, *A. facetoides* is found at Hararghe (Abebe 1987; Crowe and Gebremedhin 1984; Greathead 1966; Mendesil 2019) coffee producing areas. *Antestiopsis oribitalis* was recorded in Gomma district (JARC 2023) and its presence was confirmed, 50 years ago in a semi-plantation coffee farm. In addition, marmorated stink and *Agonoscelis* spp. was recorded on coffee trees during dry to rainy transition period at Jimma, but its crop damage was not yet been confirmed (Shimales, unpublished data). Some insect pests like Antestia bugs and coffee berry moth increase its geographical distribution from lowland to highland areas (Shimales 2019; Shimales et al. 2023b). This could be due to farming practices, changes from traditional to modern practices, and the current climate change.

Economically, Antestia bugs (*A. intricata* and *A. facetoides*) are more serious pest when coffee plants are grown under shade trees and at lowland coffee growing areas (Abebe 1987). Antestia bugs affect coffee by sucking green berries, flower buds, and growing tips, which results in blackening of coffee flowers and flower buds, fall of immature berries, and length of the internodes becoming short (Crowe and Tadesse 1984; Le Pelley 1968; Shimales and Beksisa 2021). The infestation by *A. intricata* shows a strong correlation with yield loss which was assessed to 9% (Tadesse et al. 1993). This pest also reduces the coffee quality. Some studies showed that Antestia bugs caused up to 48% darkened coffee beans (IAR 1996). Chichaybelu (2008) reported that four pairs of Antestia bugs per branch might cause up to 54% berry drop and 90% berry damage. Antestia bugs passed the threshold in an intensively managed coffee production system including Limmu Kosa estate farm compared to semi-forest and semi-plantation coffee systems (Shimales et al. 2023b). This could be due to management practices applied in commercial farming system increasing the insect. The detailed distribution, life history, economic impact, and control measures of the pest have been reviewed by Babin et al. (2018).

Soapberry bugs (*Leptocoris affinis*).

The adult *Leptocoris affinis* is reddish-brown and nymphs have a bright red abdomen with a brown-black head. It was recorded in two zones (Jimma and Guji) of coffee growing areas (Fig. 4).

Fig. 4. Soapberry bugs on coffee leaf (A), Adults and nymphs (B) from left to right.

Coffee berry borer, *Hypothemus hampei*.

In Ethiopia, the first occurrence of *H. hampei* was reported by Davidson (1965). Later on, its incidence was reported from various parts of the country (Abebe 1987, Abedeta et al. 2011; Mendesil et al. 2003, 2004, 2008; Shimales 2019). The biology, population dynamics and impact of coffee berry borer was reviewed by Mendesil et al. (2008) and Mendesil, (2019). The damage caused by coffee berry borer was higher in plantation coffee as compared to forest coffee farms. The study indicated that coffee berry borer was the most detected berry boring insect with mean proportion of 27.8% during wet and 52.88% during dry seasons in commercial coffee production system (Shimales 2019).

Coffee berry moth, *Prophantis smaragdina*.

Coffee berry moth is a minor pest; however, heavy losses of berries have been documented due to severe attacks at low altitudes (Mendesil et al. 2008). Significant berry loss has been recorded at a high-altitude of 1900 m above sea level of the Gera site in the 2023 growing season (JARC 2023).

Coffee berry moth attacks when the berries are in cluster form or webbed together. This insect pest might feed also on the tips of green branches. The berry moth symptom on berries is brown, dry or hollow (Waller et al. 2007; Crowe and Gebremedhin 1984). In the absence of berries, it may also feed on the tips of green branches.

The percentage of infested berries due to coffee berry moth ranged from 1.11% to 54.13% in 2022/23 at the Gera research sub-center (JARC 2023 unpublished data). These data have been not published yet whenever only the summary of the findings has been reported. Significant variation was observed among Limmu coffee genotypes against coffee berry moth at Gera research center (Fig. 5). The difference in infestation level among genotypes might occurred due to the difference in defense mechanism of the genotypes to coffee berry moth; this could be the future research works to develop tolerant coffee varieties against berry moth as one component of integrated pest management.

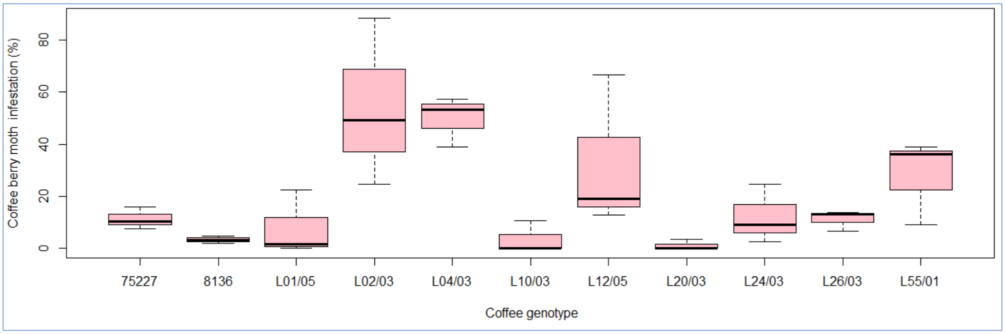

Fig. 5. Coffee berry moth damage variation among different Limu coffee genotypes at Gera in 2022/23 growing season.

Damaged berries by coffee berry moth may be an avenue for disease infection. Larval damage favors coffee berry disease infection and the silk webbing prevents the efficient use of fungicide (Crowe 2004). At Jimma (Melko), Gera and Agaro coffee research sites, the infection of coffee thread blight is highly observed on coffee berry moth infested berries (Personal observation). This might make coffee berry moth enhances and facilitates coffee thread blight infection (Personal observation).

Stem and branch borers.

Till know, seven insect species of coffee branch and stem boring insects are reported in Ethiopia, namely white coffee stem borer (*Monochamus leuconotus*), black borer (*Apate indistincta* and *Apate indistincta*), cocoa stem borer (*Eulophonotus myrmeleon)*, branch borer (*Ethmia iphicartes)*, cossid stem borer (*Duomitus* sp.) and *Xyleborus xanthopus* (Abebe 1987). Among stem and branch borer insect pests, branch borer was common at Melko on short internode coffee genotypes, while cacao stem borer has infested coffee at Mettu, Gera and Omonada district (JARC 2023). The infestation of stem borer was higher in western coffee growing areas of Ethiopia in open coffee farm (Shimales et al. 2017). The detail biology of cacao stems borer was reviewed by Mendesil (2019) and Mendesil et al. (2008). Coffee stem borer also dries the coffee stem when the plant is heavily infested. Nevertheless, there are various factors drying coffee stem and branch including over bearing, fungal diseases (coffee wilt diseases and coffee thread blight), coffee thrips and frost.

Biting ant *Tetramorium aculeatum*.

There are diverse ant species in coffee farms in Ethiopia. However, the roles of arboreal ants in coffee ecosystems are not well studied and documented in the country. Ants are a nuisance to humans in the time of coffee farm field management starting from planting to harvesting. Two arboreal ant species, the biting ant (*Tetramorium aculeatum)* and the weaver ant (*Oecophylla longinoda*), were reported from Bebeka and Tepi coffee plantations farms in southwestern Ethiopia (Damte and Minase 2010)**.** The ecological distribution of the biting ant (Kidanu 2019) and that of acrobatic ant (*Crematogaster* sp.) (Stüber et al. 2021) was studied in different management gradients of southwestern Ethiopia. In

Ethiopia, biting ants are more abundant in coffee plantations such as Tepi and Bebeka in southwestern Ethiopia (Damte and Minase 2010).

Ants biting and stinging field workers, hinder harvesting and pruning, reduce picking efficiency, increase the cost of labour, and could reduce coffee quality and yield. Yield loss due to biting ant is estimated to be 15-30% at Bebeka coffee farms (Fisseha 2014; Getachew et al. 2015). Use some insecticides including oxymatrine, nimbicidine and deltamethrin resulted in significant differences in biting ant (*T. aculeatum)* mortality and reduction of active nests (Getachew et al. 2015; Kidanu et al. 2021).

MANAGEMENT AND CONTROL

Cultural method.

Shade-tree management.

A large percentage of coffee in Ethiopia is produced in the shade. In this regard, compared to our country and other coffee producing countries, the damage caused by coffee arthropod pests in Ethiopia is less. Therefore, coffee shade can prevent some insects from multiplying and also facilitate the increase of naturally beneficial insects to control coffee insect pests below economic threshold level (Medeiros et al. 2019, Burger et al. 2021; Shimales et al. 2023a).

For example, above threshold level of Antestia bug has been recorded at Beha Land Agro Industry, commercial coffee farm located in Keffa in sun coffee farm, compared to shaded coffee farm (Shimales et al. 2023b). Shading trees (*Albizia schimperiana* and *Acacia abyssinica*) significantly lowered the severity and population density of coffee thrips, as compared to sun system, with a mean difference of above 60% (Shimales et al. 2023b). The cultural practices shade-tree regulation and pruning of coffee trees are used to minimize the effect of coffee insect pests such as Antestia bug, coffee berry borer, coffee leaf miner, coffee berry moth, coffee thrips and scale insects (Abebe 1987; Chichaybelu 2008; Crowe and Gebremedhin 1984; Mendesil et al. 2008; Shimales 2023b; Shimales and Beksisa 2021).

Conservation of natural enemies through plant diversification.

Conservation of available natural enemies through diversifying coffee farms is very important. There is no need to introduce new species as biological control agents for coffee insect pests in Ethiopia. The coffee production systems had clear impact on the parasitism rate, with a much higher parasitoid diversity in more diversified coffee farms like forests than in intensively managed plantations (Shimales et al. 2023a). For example, beneficial insects like parasitoids and predators (ants and birds) are often more abundant in less managed production systems than in intensively managed systems (Burger et al. 2021; Jonsson et al. 2015; Medeiros et al. 2019; Shimales et al. 2023a; Whitehouse et al. 2018). The Observational? studies conducted at Jimma agricultural research center (Melko), indicated that high level of larval parasitism was recorded in desmodium cover crop, and in shaded coffee farms.

Mechanical method.

Handpicking.

Handpicking of Antestia bugs and removal of their eggs from coffee parts has been recommended for Antestia pest management (Crowe 1984; Shimales and Beksisa 2021). In addition, among leaf feeder coffee, blotch miner and serpentine leaf miner are serious pests at seedling stage, especially in green house and lath house (JARC 2023). Therefore, hand squeezing of larvae at seedling stage has been recommended for control of coffee blotch miner (Shimales and Beksisa 2021).

Supplementary irrigation/Moisture conservation practices.

Irrigating coffee plants during dry periods can manage the population and severity of coffee pests. The incidence and severity of coffee thrips were higher under a full-sun system than supplementary irrigated coffee at Melko, with a mean difference of 54.55% (Shimales et al. 2023b). Shimales et al. (2021) observed a significant reduction in the severity of coffee blotch miner under well-watered than water-stressed Limmu coffee genotypes. Besides, moisture-conserving practices including mulching materials (vetiver grass and brachiaria grass), cover crop (*Desmodium* spp.) and permanent shade trees are some of the cultural practices recommended for the management of coffee thrips and coffee blotch miner (Shimales and Beksisa 2021; Shimales et al. 2021).

Proper harvesting and drying.

For berry feeding insects including coffee berry borer, proper harvesting is recommended for coffee pests (Abebe 1987; Mendesil 2019; Mendesil et al. 2003; 2004).

Biological control.

Coffee insect pests parasitoids are already present in different coffee production systems in the country, regardless of their abundance from one production system to another production type (Shimales et al., 2022). Therefore, it is necessary to conserve the already available natural enemies through diversifying coffee farms. In Ethiopia, two economically important pests, Antestia bug and coffee blotch miner, might be controlled by natural agents (Table 2). Shimales et al. (2023a) also reported different parasitoid families parasitizing coffee blotch miner larvae, with the majority of parasitoids belonging to the families of Encyrtidae.

Chemical control.

Several insects found in the coffee agroforestry system are not pests, and many are even beneficial (parasitoids, predators, beneficial fungus like entomophatogenic fungi), because they feed upon the coffee pest species. This control options might be used only when it is indispensable to be applied according the advice of a plant protection specialist. Recently, there were some recommended insecticides for insect pests of seedlings and field pests. Two botanical insecticides, oxymatrine and nimbicidine, and one synthetic insecticide deltamethrin resulted in significant differences in ant (*T. aculeatum)* mortality and reduction of active nests (Getachew et al. 2015; Kidanu et al. 2021). The two botanical insecticides i.e., oxymatrine and nimbicidine have been recommended and effective against coffee thrips control at field conditions (Shimales and Alemayehu 2018). These insecticides were also tested and recommended for control of seedling pests including coffee leaf skeletonizer, coffee blotch miner, serpertine leaf miner, giant looper caterpillar and cutworms (Shimales 2024, unpublished).

Future prospective.

A number of insects found in coffee agroforestry system are not pests and many are even beneficial as they feed upon the coffee pest species. Identifying important areas for natural enemy is key element in ecological pest management method. Hence, creating welcoming environment for natural enemies through agroforestry system (permanent shade tree), using cover crops (e.g., desmodium) and soil moisture conservation practices like mulch and supplementary irrigation could help the role of biological control agents in pest management strategies. It is essential to conserve the already available natural enemies through diversifying coffee farms as arabica coffee is originated in Ethiopia, various natural enemies could co-evolve with coffee pests. Chemical control should be used only when essential and preferably with the advice of a plant protection specialist. In future, identifying the impacts of climate change on coffee associated insect species, and mass rearing and release of natural control agents could allow for the sustainable production of coffee in Ethiopia. Besides, development of tolerant or resistant coffee varieties against economically important insect pest should have priority as an important option in the integrated pest management. Further studies are recommended especially on ecological pest management (pesticide free pest management option) strategies.

Table 2. Biological control agents (parasitoids and pathogens) of coffee pests

Natural enemies	Parasitize insect stage	Source
Asolcus suranus	Antestia eggs	Abebe 1987
Hadronotus antestiae	Antestia eggs	
Anastotus antestiae	Antestia eggs	
Corioxenos antestiae	Antestia adults	
Bogosia rubens	Antestia adults	
Entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*)	Antestia adults and nymphs	Abate 2018; Kidanu et al. 2023; Shimales et al. 2017
Aphidencyrtus aphidivorus	Coffee blotch miner larvae	Mendesil et al. 2011
Pediobius caffeicola		
Chrysocharis lepelleyi		
Apanteles bordaget		
Achrysocharis ritchiei		
Elasmus johnstoni		
Cirrospilus afer		
Bathyaulux sp.	Coffee stem borer adults	Abebe 1999

RESUME

Shimales, T., et Alemayehu D. 2024. Arthropodes ravageurs du caféier arabica et leur gestion en Ethiopie: Etat actuel et perspectives d'avenir. Tunisian Journal of Plant Protection 19 (2): 69-85.

Le caféier arabica (*Coffea arabica*) est l'une des denrées les plus importantes qui est cultivée dans diverses agroécologies d'Éthiopie. La nature pérenne et persistante du caféier favorise les attaques de plusieurs insectes, maladies, acariens et certains gastéropodes tels que les escargots et les limaces. Toutes les parties des plantes sont susceptibles d'être attaquées et des dégâts peuvent apparaître à différents stades de croissance des cultures. Les insectes du caféier endommagent les semis, réduisent le rendement du caféier et la qualité du café. De nombreux insectes trouvés dans le système agroforestier du caféier ne sont pas des ravageurs; beaucoup sont même bénéfiques car ils se nourrissent d'espèces de ravageurs du caféier. Dans le monde, plus de 3000 insectes et acariens sont associés au caféier. En Éthiopie, plus de 59 arthropodes nuisibles ont été identifiés et documentés dans le caféier de 1966 à nos jours. Parmi les arthropodes du caféier arabica identifiés dans le pays, environ 30,51 % appartiennent à l'ordre des hémiptères, tandis que 28,81 % appartiennent à l'ordre des lépidoptères. L'orthezia des serres (*Insignorthezia insignis*), les cochenilles farineuses (*Planococcus* spp. et *Pseudococcus* spp.) et les aleurodes des serres (*Trialeurodes* spp.) sont les ravageurs actuellement recensés en Éthiopie. En outre, en raison de l'évolution de la dynamique des exploitations agricoles et du changement climatique actuel, certains ravageurs auparavant peu courants, commencent à apparaître et sont discutés dans cette revue. Les insectes ravageurs du caféier sont plus problématiques dans le système de plantation de caféier. Les options de gestion des ravageurs sans pesticides dans des conditions climatiques changeantes sont cruciales. En tant que perspective d'avenir, il est très important de conserver les ennemis naturels par la diversification dans les plantations de caféier. À l'avenir, l'identification des impacts du changement climatique sur les espèces d'insectes associées au caféier, ainsi que l'élevage en masse et la libération d'agents de lutte naturels pourraient permettre une production durable en Éthiopie. Par conséquent, cette revue présente l'état passé et actuel des ravageurs des arthropodes du caféier et les options de leur gestion en Éthiopie.

Mots clés: Caféier arabica, arthropodes ravageurs, systèmes de culture, Éthiopie, management des ravageurs

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ملخص

شيماليس، تاميرو وديساليغن وأليمايهو. 2024. الآفات المفصلية للبن العربي وإدارتها في إثيوبيا: الوضع الحالي والآفاق المستقبلية.
Tunisian Journal of Plant Protection 19 (2): 69-85.

يعد البن العربي (*Coffea arabica*) أحد أهم المحاصيل التي تتم زراعتها في مختلف البيئات الزراعية في إثيوبيا. إن الطبيعة المعمرة والمستديمة لشجرة البن تسهّل هجمات العديد من الحشرات والأمراض والعناكب وبعض بطنيات الأقدام مثل الحلازين والرخويات. جميع أجزاء نبات البن معرضة للهجوم ويمكن أن تظهر الأضرار خلال مراحل مختلفة من نمو المحصول. تلحق حشرات البن الضرر بالشتلات، وتقلل من إنتاجية المحصول وجودة القهوة. العديد من الحشرات الموجودة في نظام زراعات البن الغابية ليست آفات؛ بل إن الكثير منها مفيد لأنها تتغذى على أنواع من آفات البن. في جميع أنحاء العالم، ترتبط أكثر من 3000 حشرة وعنكبوت بنبات البن. وفي إثيوبيا، تم تشخيص أكثر من 59 آفة مفصلية وتوثيقها على البن منذ عام 1966 حتى الوقت الحاضر. من بين مفصليات البن العربي التي تم تحديدها في البلاد، ينتمي حوالي 30.51% إلى رتبة نصفيات الأجنحة، في حين ينتمي 28.81% إلى رتبة حرشفيات الأجنحة. تعتبر أورثيزيا البيوت المحمية (*Insignorthezia insignis*)، والبق الدقيقي (.*Planococcus* spp و.*Pseudococcus* spp) والذباب الأبيض للبيوت المحمية (.*Trialeurodes* spp) هي الآفات المسجلة حاليًا في إثيوبيا. بالإضافة إلى ذلك، وبسبب تطور ديناميكيات الزراعة وتغير المناخ الحالي، بدأت بعض الآفات غير الشائعة في الظهور وتمت مناقشتها في هذه المراجعة. تعتبر آفات حشرات البن أكثر إشكالية في نظام زراعة مزارع البن. تعد خيارات إدارة الآفات بدون مبيدات حشرية في ظل الظروف المناخية المتغيرة أمرًا بالغ الأهمية. كمنظور مستقبلي، من المهم جدًا الحفاظ على الأعداء الطبيعيين من خلال التنويع في مزارع البن. في المستقبل، تحديد آثار تغير المناخ على أنواع الحشرات المرتبطة بالبن، إلى جانب التربية الجماعية وإطلاق عوامل المكافحة الطبيعية، يمكن أن يؤدي إلى إنتاج مستدام في إثيوبيا. لذلك، تعرض هذه المراجعة الوضع السابق والحالي لآفات مفصليات البن وخيارات إدارتها في إثيوبيا.

كلمات مفتاحية: إثيوبيا، إدارة الآفات، آفات مفصلية، بن عربي، نظم زراعية

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Enhancing Plantation Productivity: A Screen-house Investigation into the Impact of Indaziflam on Amaranthus, Maize, Melon, and Tomato in Intercropping Systems

Isesele John Imomoh, Department of Crop Science, Faculty of Agriculture, University of Benin, Benin City, Nigeria**, Olatunde Philip Ayodele,** Institute of Agricultural Research and Training (IAR&T), Obafemi Awolowo University, PMB 5029 Moor Plantation, Ibadan, Nigeria**, Celestine Ebehiremhe Ikuenobe,** Agronomy Division, Nigerian Institute for Oil Palm Research, P.M.B. 1030, Benin City, Nigeria
https://dx.doi.org/10.4314/tjpp.v19i2.3 **(*Nigeria*)**

ABSTRACT

Imomoh, I.J., Ayodele, O.P., and Ikuenobe, C.E. 2024. Enhancing plantation productivity: A screen-house investigation into the impact of indaziflam on amaranthus, maize, melon, and tomato in intercropping systems. Tunisian Journal of Plant Protection 19 (2): 87-100.

The potential impact of the new indaziflam pre-emergence herbicide on common plantation intercrops of amaranthus, maize, melon, and tomato, was assessed in a screenhouse study. The experimental treatments comprised the following inclusion of indaziflam to soil at sowing: 0, 0.15, 0.30, 0.45, 0.60, and 0.75 mg/kg. These treatments were laid out in a completely randomized design with four replications. The effect of indaziflam was evaluated through destructive sampling after 8 weeks of growth, and its residual effect was examined post-replanting after the same period, specifically at 16 weeks following indaziflam application. Data on plant height, number of leaves, leaf area, plant fresh weight, and plant dry weight were recorded in each planting instance. The collected data were subjected to analysis of variance, and the treatment means were separated using Duncan's New Multiple Range Test at a significance level of 5%. The study revealed significant reductions ($p \leq 0.05$) in growth of the test crops due to indaziflam application, with the most pronounced effects at higher concentrations. Amaranthus and tomato seedlings failed to emerge at concentrations > 0.15 mg/kg and ≥ 0.15 mg/kg, respectively. Maize and melon exhibited reduced growth at concentrations > 0.3 mg/kg. Residual effects were significant, notably reducing plant growth parameters at higher indaziflam concentrations, particularly at 0.6 and 0.75 mg/kg. In conclusion, indaziflam at concentrations greater than 0.15 mg/kg significantly inhibits the growth of common plantation intercrops, with persistent residual effects, suggesting its limited suitability for use in such contexts.

Keywords: Herbicide persistence, indaziflam, intercropping, plantation, pre-emergence herbicide

Establishing and maintaining permanent crops often face challenges associated with the vigorous growth of weeds, especially during the critical early stages. The absence of canopy cover in newly planted fields exposes them to intense weed competition (Kumar et al. 2023), making it imperative to implement effective weed management strategies to successfully establish crops. Weeds in

Corresponding author: Olatunde Philip Ayodele
Email: opayodele@iart.gov.ng

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plantations present substantial hurdles to both crop productivity and quality. Hence, implementing effective weed management strategies is essential to alleviate these concerns and optimize crop production. One promising approach to enhance productivity and diversify yields in plantation is intercropping. This cropping system involves cultivating multiple crops simultaneously on the same land (Ha et al. 2024). Intercropping offers several advantages, including reduced dependence on monoculture, improved soil fertility management, and efficient weed control (Vlahova 2022). However, the successful adoption of intercropping needs a profound understanding of crop-crop interactions and their responses to various management practices, including the judicious use of herbicides.

Indaziflam (N-[(1R,2S)-2,3-dihydro-2,6-dimethyl-1H-inden-1-yl]-6-[(1R)-1-fluoroethyl]-1,3,5-triazine-2,4-diamine), an alkylazine herbicide renowned for its distinctive capacity to selectively control both monocots and dicots (Sebastian et al. 2017), has emerged as a viable solution for weed management during the initial phases of tree crop establishment (Grey et al. 2016). Its protracted residual activity and efficacy against a broad spectrum of weed species position it as a compelling candidate for augmenting weed suppression in plantation agriculture. Moreover, unlike many pre-emergence herbicides, indaziflam exhibits a longer soil half-life of over 150 days (Kaapro and Hall 2012). Notably, indaziflam ability to effectively inhibit cellulose biosynthesis makes it a suitable option for weed control (Jeschke 2022). The tolerance demonstrated by tree crops adds to their potential suitability for integration into intercropping and multiple cropping systems. Nevertheless, safeguarding susceptible crops within these cropping systems remains essential.

The persistence of herbicides applied to soil varies by location due to environmental and biological differences (Das 2024). Therefore, it is essential to evaluate crop response when introducing a herbicide to a new region. Indaziflam has recently become available in Nigeria for pre-release testing. However, the use of indaziflam does not come without challenges. A study conducted in North Carolina, USA, has revealed that even at a low simulated indaziflam drift rate of 2.5%, off-target plant injury risk remains a concern. For example, this low drift rate resulted in greater than 20% root mass reduction in several crops, including cotton, bell pepper, soybean, squash, and tomato (Jeffries et al. 2014). While indaziflam shows promise for use in monocropping systems involving tolerant tree crops, these findings underscore the importance of thoroughly understanding its potential impact on non-target intercrops and rotational crops.

Given the potential phytotoxic effects of indaziflam on non-target crops, this study embarked on a comprehensive exploration to assess its impact on the growth of amaranthus, maize, melon, and tomato. These crops are frequently grown as intercrops in Nigerian plantations, and the study specifically aimed to evaluate their suitability for intercropping and multiple cropping systems.

MATERIALS AND METHODS

Materials.

Seeds of amaranthus (*Amaranthus hybridus*, cv. NH84/457-IL), maize (*Zea mays*, cv. Ak 96 dmr sr-w), melon (*Cucumis melo*, cv. URANUS F1), and tomato (*Solanum lycopersicum*, cv. ROMA VF) were sourced from the Agricultural Development Project (ADP) Office in Benin City. The topsoil, used as the growing medium for the test crops, was collected from the University of Benin

Teaching and Research Farm. Alion® herbicide, formulated as 19.05% indaziflam in soluble concentrate was supplied by Bayer CropScience.

Preparation of a standardized stock solution.

A standardized stock solution of indaziflam was prepared meticulously at the Chemistry Laboratory of the Nigerian Institute for Oil Palm Research (NIFOR), located near Benin City. Through a series of precise and calibrated serial dilutions, concentrations of 0.2, 0.4, 0.6, 0.8, and 1 mg/L of indaziflam were prepared such that, when 250 ml of each was applied directly to the soil, the desired experimental treatment was achieved.

Experimental site.

The study was conducted within a screenhouse at the Teaching and Research Farm of the University of Benin, Benin City, situated in the humid rainforest zone of southern Nigeria (latitude 6.02°N and longitude 5.06°E). The experiments were carried out from March to June 2016, during which meteorological data indicated temperatures ranging from 24.5 to 32.7°C, with a mean of 28.6°C. Relative humidity fluctuated between 63.31 and 81.71%, while daily sunshine duration varied from 5.85 to 7.50 hours. The topsoil, sieved using a 2 mm mesh, was used to fill pots arranged in the screenhouse. Each pot, measuring 12 cm in depth, 7 cm in top diameter, and 4.5 cm in basal diameter, contained 311 cm^3 (0.3 kg) of sieved topsoil arranged in a 5 × 15 cm spacing within the screenhouse. The soil detailed physico-chemical characteristics are presented in Table 1.

Table 1. Physico-chemical properties of pre-treatment soil

Parameter	Value
pH in (H_20)	5.60
Total Nitrogen (g/kg)	2.80
Available P (mg/kg)	2.55
Organic carbon (g/kg)	17.76
Organic matter (g/kg)	30.62
CEC (cmol/kg)	4.63
ECEC (cmol/kg)	5.16
Ca (cmol/kg)	0.25
Mg (cmol/kg)	0.22
K (cmol/kg)	0.43
Na (cmol/kg)	0.19
Silt (%)	9.42
Sand (%)	73.95
Clay (%)	16.60
Textural class	Sandy loam
Exchange Acidity (cmol/kg)	2.03
Base saturation (%)	58.57

Seeds viability test.

Initial seed viability test was thoroughly conducted by immersing the seeds of selected crops in water within a bowl and hand-picking the submerged seeds. Following this careful selection process, the seeds were gently air-dried before being used for planting.

Experimental design and treatments.

The experiment was set up following a completely randomized design, with the experimental treatments consisting of six doses of indaziflam (0, 0.15, 0.30, 0.45, 0.60, and 0.75 mg/kg soil). These concentrations were obtained by applying dilutions of Alion® (indaziflam herbicide) to appropriate quantity of soil. Twenty-four pots were allocated for cultivating each of maize, melon, amaranthus, and tomato, with experimental treatments replicated four times, totaling ninety-six pots.This layout ensured separate and distinct evaluations for each crop and dose combination. After applying indaziflam at each dose, three seeds of each crop were sown in twenty-four pots at a depth of approximately 3 cm. Following the emergence of the seedlings, multiple seedling stands were thinned down to one plant per pot 2 weeks after sowing.

Growth parameter measurement.

At 8 weeks after treatmant, data were collected on various variables. Plant height (cm), number of leaves, leaf area (cm^2), fresh weight (g), and dry weight (g) of plants were measured. Plant height was determined using a measuring tape from the base to the tip. The number of leaves per pot was counted, and leaf area was determined following the method of Gates (1991). Plants were carefully removed by hand for fresh weight measurement, and the soil sticking to the root region was washed back into the pots with clean water. The plants were weighed using an electronic precision balance (Kerro BL 2001). Dry weights were obtained by oven-drying the harvested plants at 80ºC until a constant weight was achieved.

Follow-up trial.

Following the termination of the initial experiment at 8 weeks after treatmant, a subsequent follow-up trial was conducted using the same pots for replanting, with no additional application of indaziflam. Data were collected similarly to the first trial at 8 weeks after treatmant, coinciding with 16 weeks after the treatment application.

Data analysis.

The data obtained from the trials were analyzed using Genstat 8 software through analysis of variance. The treatment means were then separated using the Duncan New Multiple Range Test (DNMRT) at a 5% probability level.

RESULTS

Effects of indaziflam and its residues on the growth of amaranthus.

At 8 weeks after treatment and sowing, the application of indaziflam resulted in a significant reduction ($p \leq 0.05$) in various growth parameters of the amaranthus plant (Tables 2, 3). These parameters included plant height, number of leaves, leaf area, as well as fresh and dry weights. Visible reduction in these growth parameters was observed specifically at indaziflam level of 0.15 mg/kg soil. Notably, amaranthus seedlings failed to emerge in pots treated with indaziflam concentrations greater than 0.15 mg/kg soil.

At 8 weeks after re-sowing, corresponding to 16 weeks after treatment, the height of the amaranthus plant showed a significant reduction ($p \leq 0.05$) due to the residues from concentrations of indaziflam greater than 0.15 mg/kg soil. Additionally, it was observed that the indaziflam residues from 0.15, 0.3, 0.45 mg/kg of soil significantly reduced the number of leaves, leaf area, and the plant fresh and dry weights. The extent of reduction in the amaranthus growth parameters exhibited an upward trend as the concentrations of indaziflam increased Remarkably, amaranthus seedlings did not emerge in pots containing indaziflam residues from 0.75 mg/kg of soil (Tables 2, 3).

Table 2. Effect of indaziflam and its residues on growth of amaranthus

Indaziflam dose (mg/kg soil)	Plant height (cm)	Number of leaves	Leaf Area (cm^2)	Fresh plant weight (g)	Dry plant weight (g)
8 weeks after treatment					
0	18.68a	13.00a	23.90a	13.54a	4.07a
0.15	0.50b	1.00b	0.12b	0.00b	0.00b
0.3	0.00b	0.00b	0.00b	0.00b	0.00b
0.45	0.00b	0.00b	0.00b	0.00b	0.00b
0.6	0.00b	0.00b	0.00b	0.00b	0.00b
0.75	0.00b	0.00b	0.00b	0.00b	0.00b
SE±	0.38	0.57	0.31	0.53	0.16
16 weeks after treatment					
0	14.00a	12.00a	14.68a	16.30a	4.90a
0.15	12.25a	7.00bc	6.58b	10.80b	2.20b
0.3	7.75b	5.00cd	6.45b	2.20c	0.00c
0.45	7.25b	8.00b	5.57b	1.10d	0.00c
0.6	1.50c	2.00de	0.57c	0.00e	0.00c
0.75	0.00c	0.00e	0.00c	0.00e	0.00c
SE±	0.98	0.92	0.68	0.54	0.01

Means in a column followed by similar letters are not significantly different at 5% level of probability by Duncan's New Multiple Range Test (DNMRT).

Table 3. Symbolic depictition of the effect of indaziflam and its residues on growth of amaranthus

Amaranthus	**8 weeks after treatment**						**16 weeks after treatment**					
	Indaziflam dose (mg/kg soil)											
	0	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**	**0**	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**
Plant height (cm)	18.68	-	-	-	-	-	14.00	*	-	-	-	-
Number of leaves	13.00	-	-	-	-	-	12.00	-	-	-	-	-
Leaf area (cm^2)	23.90	-	-	-	-	-	14.68	-	-	-	-	-
Fresh plant weight (g)	13.54	-	-	-	-	-	16.30	-	-	-	-	-
Dry plant weight (g)	4.07	-	-	-	-	-	4.90	-	-	-	-	-

Symbols: * indicates no significant difference from the control, and - indicates a value significantly lower than the control, based on Duncan's New Multiple Range Test (DNMRT) at the $p = 0.05$ significance level.

Effects of indaziflam and its residues on the growth of maize.

At the 8 week after planting and treatment application, it became evident that varying concentrations of indaziflam significantly influenced critical parameters of maize growth (Tables 4, 5). Maize plant height experienced a notable reduction ($p \leq 0.05$) due to indaziflam concentrations, showing a corresponding decrease in height as herbicide concentration increased. The most substantial decrease occurred at 0.6 mg of indaziflam per kg of soil, as maize seedlings failed to emerge in pots treated with higher concentration. Similarly, the number of leaves per plant demonstrated reductions linked to indaziflam concentrations, except for 0.15 and 0.3 mg/kg. This reduction in leaf count exhibited an upward trend with increasing herbicide concentration. Furthermore, the impact of different indaziflam concentrations (0.15, 0.3, 0.45, 0.6, 0.75 mg/kg) on maize leaf area and fresh plant weight was notable, revealing statistically significant reductions ($p \leq 0.05$) across all concentrations. Notably, as the herbicide concentration increased, the leaf area and fresh plant weight reduction became more pronounced, with the highest reduction observed at 0.6 mg/kg and no plant emerged at 0.75 mg/kg. Moreover, the dry weight of maize plants exhibited a similar pattern, displaying significant reductions ($p \leq 0.05$) at indaziflam concentrations of 0.3, 0.45, 0.6, and 0.75 mg/kg.

Table 4. Effect of indaziflam and its residue on growth of maize

Indaziflam dose (mg/kg soil)	Plant height (cm)	Number of leaves	Leaf area (cm^2)	Fresh plant weight (g)	Dry plant weight (g)
			8 weeks after treatment		
0	29.85a	7.00a	98.70a	30.04a	10.49a
0.15	16.80b	5.00a	46.00b	25.20b	8.78a
0.3	7.90c	6.00a	16.20c	12.47c	4.34b
0.45	4.00d	2.00b	5.10cd	2.77d	0.89c
0.6	1.80de	2.00b	2.80d	0.67e	0.00d
0.75	0.00e	0.00c	0.00d	0.00e	0.00d
SE±	0.76	0.53	3.98	0.22	0.08
			16 weeks after treatment		
0	19.50a	7.00a	26.70b	12.60b	4.40bc
0.15	18.50a	7.00a	38.50a	15.50a	5.40a
0.3	17.50a	7.00a	36.50a	13.50ab	4.70ab
0.45	17.25a	6.00a	30.30ab	11.50bc	3.70c
0.6	11.25b	6.00a	22.00b	10.10c	2.90d
0.75	6.50c	4.00b	6.30c	3.30d	0.60e
SE±	1.54	0.61	2.79	1.68	0.6

Means in a column followed by similar letters are not significantly different at 5% level of probability by by Duncan’s New Multiple Range Test (DNMRT).

At 8 weeks after re-sowing, corresponding to 16 weeks after treatment application, the height of maize plants associated with residues from 0.15, 0.3, and 0.45 mg of indaziflam per kg soil exhibited comparability ($p \leq 0.05$) with the indaziflam-free treatment (control). Conversely, the residues from 0.6 and 0.75 mg/kg reduced the height of maize plants. The leaf count per maize plant was not significantly affected ($p \leq 0.05$) by the residues from0.15, 0.3, 0.45 and 0.6 mg of indaziflam per kg of soil. However, the residues of 0.75 mg/kg resulted in a reduction in maize leaf count. The leaf area of maize showed a significant increase ($p \leq 0.05$) due to residues from 0.15 and 0.3 mg of indaziflam per kg soil. Residues from 0.45 and 0.6 mg/kg resulted in a maize leaf area comparable to the indaziflam-free treatment, while 0.75 mg/kg led to a reduction in the maize leaf area. The fresh and dry weights of the maize plants experienced a significant increase due to the residue from 0.15 mg of indaziflam per kg of soil. Residues from 0.3 and 0.45 mg/kg soil yielded maize plant fresh and dry weights comparable to the indaziflam-free treatment. Conversely, residues from 0.6 and 0.75 mg of indaziflam per kg soil resulted in a notable reduction ($p \leq 0.05$) in the fresh and dry weights of the maize plants.

Table 5. Symbolic depictition of the effect of indaziflam and its residue on growth of maize

Maize	8 weeks after treatment						16 weeks after treatment					
	Indaziflam dose (mg/kg)											
	0	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**	**0**	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**
Plant height (cm)	29.85	-	-	-	-	-	19.50	*	*	*	-	-
Number of leaves	7.00	*	*	-	-	-	7.00	*	*	*	*	-
Leaf Area (cm^2)	98.70	-	-	-	-	-	26.70	+	+	*	*	-
Fresh plant weight (g)	30.04	-	-	-	-	-	12.60	+	*	*	-	-
Dry plant weight (g)	10.49	*	-	-	-	-	4.40	+	*	*	-	-

Symbols: + indicates a value significantly higher than the control, * indicates no significant difference from the control, and - indicates a value significantly lower than the control, based on Duncan's New Multiple Range Test (DNMRT) at the p = 0.05 significance level.

Effects of indaziflam and its residues on the growth of melon.

Eight weeks after treatment application, the growth of melon showed a significant reduction ($p \leq 0.05$) as a result of applying 0.15 and 0.3 mg indaziflam per kg soil during sowing (Tables 6, 7). Notably, plant height, leaf count, leaf area, and the fresh and dry weights of melon plants decreased in correspondence with the increasing concentration of the indaziflam herbicide. Indaziflam concentrations greater than 0.3 mg/kg of soil resulted in no emergence of melon seedlings.

Eight weeks after re-sowing, which aligns with 16 weeks after treatment application, the presence of residues from 0.15, 0.3 and 0.45 mg indaziflam per kg soil did not yield a significant impact on the plant height and leaf count per melon plant in comparison to the indaziflam-free treatment. However, residues from 0.6 mg indaziflam per kg soil significantly reduced melon plant height. Additionally, residues from 0.75 mg indaziflam per kg soil resulted in no emergence of melonseedling. Residues from concentrations of indaziflam greater than 0.15 mg/kg significantly decreased ($p \leq 0.05$) the leaf area of melon. The dry and fresh weights of the melon plant exhibited a significant increase ($p \leq 0.05$) due to the presence of residues from low concentrations of indaziflam (0.15 and 0.3 mg/kg). Residues from 0.45 mg indaziflam per kg soil did not yield a significant impact ($p \leq 0.05$) on the dry and fresh weights of the melon plant. However, residues from 0.6 mg/kg significantly reduced ($p \leq 0.05$) both the dry and fresh weights of the melon plant.

Table 6. Effect of indaziflam and its residue on growth of melon

Indaziflam dose (mg/kg)	Plant height (cm)	Number of leaves	Leaf Area (cm^2)	Fresh plant weight (g)	Dry plant weight (g)
	8 weeks after treatment				
0	84.50a	21.00a	44.62a	5.60a	1.98a
0.15	7.00b	3.00b	4.01b	0.00b	0.00b
0.3	6.00b	2.00b	3.58b	0.00b	0.00b
0.45	0.00b	0.00b	0.00b	0.00b	0.00b
0.6	0.00b	0.00b	0.00b	0.00b	0.00b
0.75	0.00b	0.00b	0.00b	0.00b	0.00b
SE±	7.45	1.76	1.91	0.23	0.78
16 weeks after treatment					
0	28.20a	7.00a	63.00a	5.50b	1.30b
0.15	24.00a	8.00a	61.00a	7.70a	1.50a
0.3	23.00a	8.00a	31.00b	8.90a	1.80a
0.45	22.00ab	8.00a	22.50bc	5.70b	1.30b
0.6	14.20b	5.00a	14.40c	4.30c	0.90c
0.75	0.00c	0.00b	0.00d	0.00d	0.00d
SE±	2.81	0.94	3.84	1.89	0.13

Means in a column followed by similar letters are not significantly different at 5% level of probability by Duncan's New Multiple Range Test (DNMRT).

Table 7. Symbolic depictition of the effect of indaziflam and its residue on growth of melon

Melon	8 weeks after treatment						16 weeks after treatment					
	Indaziflam dose (mg/kg)											
	0	0.15	0.3	0.45	0.6	0.75	0	0.15	0.3	0.45	0.6	0.75
Plant height	84.50	-	-	-	-	-	28.20	*	*	*	-	-
Number of leaves	21.00	-	-	-	-	-	7.00	*	*	*	*	-
Leaf Area (cm^2)	44.62	-	-	-	-	-	63.00	*	-	-	-	-
Fresh plant weight (g)	5.60	-	-	-	-	-	5.50	+	+	*	-	-
Dry plant weight (g)	1.98	-	-	-	-	-	1.30	+	+	*	-	-

Symbols: + indicates a value significantly higher than the control, * indicates no significant difference from the control, and - indicates a value significantly lower than the control, based on Duncan's New Multiple Range Test (DNMRT) at the p = 0.05 significance level.

Effects of indaziflam and its residues on the growth of tomato.

At 8 weeks after sowing and treatment application, the application of indaziflam at concentrations of 0.15, 0.3, 0.45, 0.6 and 0.75 mg/kg resulted in no emergence of tomato plants (Tables 8, 9). This outcome unequivocally indicates that indaziflam significantly impeded ($p \leq 0.05$) the growth of tomato plants in contrast to the indaziflam-free treatment. Consequently, no observable plant height, leaf count, leaf area, or dry and fresh weights were recorded due to the indaziflam treatment.

Eight weeks postre-sowing, corresponding to 16 weeks post-treatment application, residues of 0.15 and 0.3 mg of indaziflam per kg of soil did not significantly impact the height of tomato plants. In contrast, residues from higher concentrations of indaziflam resulted in a notable reduction in the height of tomato plants. Residues from 0.15, 0.3, 0.45 and 0.6 mg indaziflam per kg soil did not significantly impact the leaf count and leaf area of tomato plants. However, the presence of residues from 0.75 mg indaziflam per kg soil significantly decreased both the leaf count and the leaf area of tomato plants. The presence of residues from 0.15 and 0.3 mg indaziflam per kg soil resulted in a notable increase in both tomato plant fresh and dry weights. In contrast, residue from 0.45 mg indaziflam per kg soil did not significantly impact the fresh and dry weights of tomato plants. However, residue from 0.75 mg indaziflam per kg soil substantially reduced the fresh and dry weights of tomato plants.

Table 8. Effect of indaziflam and its residue on growth of tomato

Indaziflam dose (mg/kg)	Plant height (cm)	Number of leaves	Leaf Area (cm^2)	Fresh plant weight (g)	Dry plant weight (g)
	8 weeks after treatment				
0	22.25a	31.00a	9.54a	16.83a	3.06a
0.15	0.00b	0.00b	0.00b	0.00b	0.00b
0.3	0.00b	0.00b	0.00b	0.00b	0.00b
0.45	0.00b	0.00b	0.00b	0.00b	0.00b
0.6	0.00b	0.00b	0.00b	0.00b	0.00b
0.75	0.00b	0.00b	0.00b	0.00b	0.00b
SE±	0	1.09	0.3	0.67	0.12
	16 weeks after treatment				
0	14.75a	20.00a	2.80b	4.40c	0.80b
0.15	16.50a	21.00a	6.82a	10.40a	1.60a
0.3	12.00ab	19.20a	4.04b	6.60b	1.20a
0.45	10.25b	18.20a	2.68b	4.00c	0.80b
0.6	7.75b	14.00a	1.82bc	2.40d	0.50b
0.75	1.12c	2.00b	0.35c	0.00e	0.00c
SE±	1.5	2.89	0.65	1.91	0.42

Means in a column followed by similar letters are not significantly different at 5% level of probability by DNMRT.

Table 9. Symbolic depictition of the effect of indaziflam and its residue on growth of tomato

Tomato	8 weeks after treatment						16 weeks after treatment					
	Indaziflam dose (mg/kg)											
	0	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**	**0**	**0.15**	**0.3**	**0.45**	**0.6**	**0.75**
Plant height (cm)	22.25	-	-	-	-	-	14.75	*	*	-	-	-
Number of leaves	31	-	-	-	-	-	20	*	*	*	*	-
Leaf Area (cm^2)	9.54	-	-	-	-	-	2.8	*	*	*	*	-
Fresh plant weight (g)	16.83	-	-	-	-	-	4.4	+	+	*	-	-
Dry plant weight (g)	3.06	-	-	-	-	-	0.8	+	+	*	*	-

Symbols: + indicates a value significantly higher than the control, * indicates no significant difference from the control, and - indicates a value significantly lower than the control, based on Duncan's New Multiple Range Test (DNMRT) at the p = 0.05 significance level.

DISCUSSION

The phytotoxicity of indaziflam, which was observed as its negative impact on plant growth, seemed to vary as the time after application progressed. While phytotoxic effects were evident shortly after application, its prevalence over time depends on the crop and the concentration of indaziflam. Some crops and indaziflam concentrations showed reduced phytotoxicity at 16 weeks after treatment, while others continued to experience negative impacts. This variation underscores the complexity of the interaction between indaziflam, plant species, and the duration after application.

At 8 weeks after treatment, the application of indaziflam at sowing reduced significantly various growth parameters of amaranthus, including plant height, leaf number, leaf area, and fresh/dry weights. This initial phytotoxicity was evident shortly after application. Interestingly, at 16 weeks after treatment, the residues of indaziflam from concentrations greater than 0.15 mg/kg continued to negatively impact amaranthus growth by reducing plant height, leaf number, leaf area, and fresh/dry weights. This persistence of phytotoxic effects indicates that indaziflam residues remained biologically active in the soil and continued to hinder amaranthus growth over an extended period. The reduction in the amaranthus growth parameters, which showed an upward trend as the concentrations of indaziflam increased, corroborates the findings of Sebastian et al. (2017), who reported that indaziflam reduced the growth of susceptible crops in a dose-dependent manner.

The phytotoxicity of indaziflam on maize was evident 8 weeks after treatment, where different concentrations reduced plant height, leaf count, leaf area, and fresh/dry weights. This impact suggests that maize is sensitive to indaziflam when planting is done shortly after indaziflam application. The response was more complex at 16 weeks after treatment. For low concentrations of indaziflam, the growth parameters showed comparability to the control treatment, indicating a reduction in phytotoxicity. This observation could be attributed to the breakdown of the low concentration of indaziflam and its decreasing concentration over time. This result corroborates the findings of Guerra et al. (2014) where maize has intermediate tolerance to indaziflam. In this study, maize exhibited higher tolerance to indaziflam when compared to amaranthus and tomato. Similarly, Braga et al. (2020) reported superior tolerance of maize over sorghum, wheat, and oats towards indaziflam. However, residues from high indaziflam concentrations (0.6 and 0.75 mg/kg) still negatively impact maize growth, suggesting that the phytotoxic effects persist for high concentrations even at 16 weeks after application.

Melon plants showed significant reductions in growth parameters at 8 weeks after treatment, indicating strong phytotoxicity shortly after indaziflam application. At 16 weeks after treatment, the effects of indaziflam residues were mixed. Residues from lower concentrations (0.15 and 0.3 mg/kg) increased dry and fresh weights, suggesting a reduction in phytotoxicity. However, residues from higher concentrations (0.6 and 0.75 mg/kg) continue to negatively affect growth, underscoring persistent phytotoxicity for high residue concentrations.

On the other hand, the most severe phytotoxicity was observed in tomato plants. At 8 weeks after treatment, all concentrations of indaziflam led to no emergence of tomato plants, indicating strong and immediate phytotoxic effects.

The impact remained consistent at 16 weeks after treatment, as residues from all concentrations continued to impede tomato growth. This indicates that indaziflam, even at lower concentrations, has a prolonged and detrimental impact on tomato plants.

Among the effects observed due to indaziflam, a noteworthy phenomenon was the emergence of increased growth of maize and melon at low concentrations. This observed increase in growth aligns with hormetic effect, where low doses of stressors or toxins stimulate beneficial effects or growth, while high doses are inhibitory (Pincelli-Souza et al. 2020). This finding agrees with the report of da Costa et al. (2020) where indaziflam is capable of stimulating plant growth. This implies that indaziflam at low concentration is beneficial to some intercrops in plantations. The stimulatory effect seen at lower indaziflam concentrations on maize and melon challenges the traditional linear dose-response model, where exposure to a toxin is deemed harmful. These findings emphasize the need for a nuanced understanding of dose-response relationships and the potential benefits of low-level stressors.

Considering the diverse susceptibility levels of amaranthus, maize, melon, and tomato to different indaziflam concentrations, it is crucial to customize the application of indaziflam by considering the individual tolerances of each crop in intercropping system. This could entail modifying the concentrations utilized or adopting alternative cultivation strategies to mitigate any potential detrimental effects on the growth of these crops. The study implies the importance of managing the persistence of indaziflam in soil to facilitate intercropping of the test crops in plantations treated with this herbicide. This supports the report of Melo et al. (2016) where persistent herbicides often pose risks to susceptible crops in rotation and intercropping systems.

Furthermore, this study suggests that maintaining a sufficient pre-plant interval between the application of indaziflam and the sowing of crops can prevent adverse effects on crop growth. This inference is drawn from the observed negative impact of indaziflam when applied at sowing and the absence of such effects when an eight-week pre-plant application interval was observed. These findings corroborate the conclusions of Soltani et al. (2011), who reported that increasing the pre-plant herbicide application interval can mitigate crop injury.

In alignment with the findings of Mendes et al. (2021), who examined the effect of cow bonechar on the herbicidal activity of indaziflam in tropical soil, it is suggested that the incorporation of cow bonechar into soil at a rate of 2 t/ha could be explored as a strategy to manage the persistence of indaziflam. This approach should be investigated further to evaluate the responses of the test crops.

In conclusion, this study showed that the use of indaziflam in intercropping system involving amaranthus, maize, melon, and tomato could negatively impact the growth of these crops.

RESUME

Imomoh I.J., Ayodele O.P. et Ikuenobe C.E. 2024. Amélioration de la productivité des plantations: Une étude sous-serre sur l'impact de l'indaziflam sur l'amarante, le maïs, le melon et la tomate dans les systèmes de cultures intercalaires. Tunisian Journal of Plant Protection 19 (2): 87-100.

L'impact potentiel du nouvel herbicide de pré-levée indaziflam sur les cultures intercalaires courantes de plantation d'amaranthe, maïs, melon et tomate, a été évalué dans une étude sous-serre. Les traitements expérimentaux comprenaient l'application suivante d'indaziflam dans le sol au semis : 0, 0,15, 0,30, 0,45, 0,60 et 0,75 mg/kg. Ces traitements ont été mis en place selon un plan complètement randomisé avec quatre répétitions. L'effet de l'indaziflam a été évalué par échantillonnage destructif après 8 semaines de croissance, et son effet résiduel a été examiné après le re-semis après la même période, plus précisément 16 semaines après l'application d'indaziflam. Les données sur la hauteur de la plante, le nombre de feuilles, la surface foliaire, le poids frais de la plante et le poids sec de la plante ont été enregistrés dans chaque cas de traitement. Les données recueillies ont été soumises à une analyse de variance et les moyennes des traitements ont été séparées à l'aide du *Duncan's New Multiple Range Test* à un niveau de signification de 5 %. L'étude a révélé des réductions significatives ($p \leq 0{,}05$) de la croissance des cultures d'essai en raison de l'application d'indaziflame, les effets les plus prononcés correspondaient aux concentrations les plus élevées. Les semis d'amarante et de tomate n'ont pas émergé à des concentrations > 0,15 mg/kg et ≥ 0,15 mg/kg, respectivement. Le maïs et le melon ont présenté une croissance réduite à des concentrations > 0,3 mg/kg. Les effets résiduels étaient significatifs, réduisant notamment les paramètres de croissance des plantes à des concentrations d'indaziflame plus élevées, en particulier à 0,6 et 0,75 mg/kg. En conclusion, l'indaziflame à des concentrations supérieures à 0,15 mg/kg inhibe significativement la croissance des cultures intercalaires des plantations courantes, avec des effets résiduels persistants, ce qui suggère son adéquation limitée à son utilisation dans de tels contextes.

Mots clés: Herbicide de pre-levée, indaziflam, intercalaire, persistance d'herbicide, semis

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ملخص

إيمومو، إيسيسيلي دجون وأولاتوندي فيليب أيوديلي وسيليستين إيبيهايريكهي إيكونوبي. 2024. تحسين إنتاجية المَزارع: دراسة في البيوت المحمية حول تأثير المبيد العشبي إندازيفلام على القطيفة والذرة والبطيخ والطماطم في أنظمة الزراعة البينية. Tunisian Journal of Plant Protection 19 (2): 87-100.

تم تقييم التأثير المحتمل للمبيد العشبي الجديد قبل البزوغ إندازيفلام على المحاصيل البينية المزروعة بشكل شائع من القطيفة والذرة والبطيخ والطماطم في دراسة تحت البيوت المحمية. تضمنت المعاملات التجريبية إضافة مبيد إندازيفلام إلى التربة عند البذر بنسب 0، 0.15، 0.30، 0.45، 0.60 و 0.75 ملغم/كغم. تم تنفيذ هذه المعاملات وفق التصميم العشوائي الكامل بأربعة مكررات. تم تقييم تأثير مبيد إندازيفلام عن طريق أخذ العينات التدميرية بعد 8 أسابيع من النمو، وتم فحص تأثيره المتبقي بعد إعادة البذر بنفس الفترة، أي 16 أسبوع بعد تطبيق المبيد. تم تسجيل بيانات عن ارتفاع النباتات وعدد الأوراق ومساحة الأوراق والوزن الطازج للنباتات والوزن الجاف للنباتات في كل حالة معاملة. تم إخضاع البيانات المجمعة لتحليل التباين وتم فصل معدلات المعاملات باستخدام اختبار دنكان الجديد متعدد المدى عند مستوى دلالة 5%. بينت الدراسة انخفاضات كبيرة ($p \geq 0.05$) في نمو نباتات الاختبار بسبب تطبيق المبيد، مع التأثيرات الأكثر وضوحًا مقابلة لأعلى التركيزات. لم تبزغ بادرات القطيفة والطماطم بتركيزات > 0.15 مجم/كجم و ≤ 0.15 مجم/كجم، على التوالي. أظهرت الذرة والبطيخ انخفاضا في النمو عند التركيزات > 0.3 ملغم/كغم. وكانت تأثيرات متبقيات المبيد كبيرة، لا سيما انخفاض مؤشرات نمو النباتات عند التركيزات الأعلى من المبيد، خاصة عند 0.6 و0.75 ملجم/كجم. في الخلاصة، أدى مبيد إندازيفلام بتركيزات أعلى من 0.15 ملغم/كغم إلى تثبيط نمو المحاصيل الزراعية الشائعة بشكل كبير، مع استمرار تأثيرات متبقياته، مما يشير إلى ملاءمته المحدودة للاستخدام في مثل هذه الحالات.

كلمات مفتاحية: مبيد عشبي قبل البزوغ، إندازيفلام، زراعات بينية، ثبات المبيد العشبي، بذر

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Impact of Nematicides on Plant-Parasitic Nematodes: Challenges and Environmental Safety

Srijan Tiwari, Department of Plant Pathology, Agriculture and Forestry University, Rampur, Chitwan, Nepal

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ABSTRACT

Tiwari, S. 2024. Impact of nematicides on plant-parasitic nematodes: Challenges and environmental safety. Tunisian Journal of Plant Protection 19 (2): 101-120.

Plant Parasitic Nematodes (PPNs) are tiny, pseudocoelomate, unsegmented, bilaterally symmetrical vermiform animals that attack plants. Nematicides are chemically synthesized substances that kill or harm nematodes. Between 1940 and 1950, three chemicals with nematicidal properties were discovered: methyl bromide (bromomethane), D-D mixture, and EDB (1, 2-dibromoethane; as ethylene dibromide) which were fumigants. When fumigant compounds are applied to soil, a gas moves through the open spaces between soil particles or into the water film that surrounds soil particles. Fumigants significantly decrease nematode respiration by oxidizing Fe^{2+} centers and alkylated proteins in the cytochrome-mediated electron transport chain. Despite the efficacy of fumigants in nematode, their use was lowered due to the high environmental risk of these products. A new generation of nematicides was introduced: carbamates and organophosphates that served as contact nematicides, which led to the testing and development of other non-fumigant nematicides such as aldicarb, carbofuran, ethoprop, and fenamiphos. The carbamates and organophosphates acetylcholinesterase inhibitory properties prevent normal nerve impulse transmission in the nematode nervous system. Nematicides are typically non-selective pesticides, and their use impacts non-target organisms, humans, and the environment. Since nematicides are toxic to humans, soil, groundwater, and non-target organisms, cautious nematicide selection and application are vital. New compounds that are less aggressive and more specific for PPNs have been developed, making them safer for the producer, consumer, and environment. Crop rotation, cover crops, organic manuring, use of resistant varieties, and other methods must be integrated with nematicides for increased effectiveness.

Keywords: Human safety, nematicides, organophosphates, plant parasitic nematodes, poisoning

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INTRODUCTION

Plant Parasitic Nematodes (PPNs) are tiny, transparent, pseudo-coelomate micro-organisms that resemble microscopic worms and can live either free or as parasites. They can be predatory, aquatic, terrestrial, entomopathogenic, ectoparasitic, endoparasitic, semi-endoparasitic (such as *Tylenchulus semipenetrans*), or stationary (Shah and Mahamood 2017). Nearly 4100 PPN species have been identified, and they are considered a significant threat to world food security (Nicol et al. 2011). While lacking circulatory function, their body has recognizable organs for the digestive, nervous, and excretory systems and a

Corresponding author: Srijan Tiwari
Email: srijantiwari03@gmail.com

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well-developed reproductive system (Souza 2008). The majority of the species are referred to as "farmers' close friends" because many of them kill insects (Shah and Mahamood 2017). Nematode damage to crops is typically difficult to detect because there are so many other variables that impede plant growth (Mitik 2018). Today, the main plant parasitic nematodes in economic terms are root-knot nematodes (*Meloidogyne* spp.), followed by cyst nematodes (*Heterodera* and *Globodera* spp.), root lesion nematodes (*Pratylenchus* spp.), burrowing nematode (*Radopholus similis*), and the stem nematode (*Ditylenchus dipsaci*) (Jones et al. 2013). Since eradication of nematodes is not possible, the goal is to manage their population and reduce their numbers below damaging levels (Mitiku 2018). Planting resistant varieties, rotating crops, adding soil nutrients, and using pesticides are a few common control strategies. The discovery that particular compounds had nematicidal qualities and their subsequent application in agriculture had a significant impact on crop production by raising crop yield and quality globally. These compounds were initially administered to the soil to sterilize it and eliminate any pests and PPNs. As a result, the employment of such chemical agents in agriculture significantly impacted agricultural productivity, increasing crop yield and quality globally (Antônio et al. 2019).

HISTORY OF NEMATICIDES

Chemical control is an important tool in nematode control. It is considered one of the most effective and reliable control techniques within integrated management (Kim et al. 2016). Chemical agents were first used in 1881, with carbon disulfide being the first product discovered as having nematicidal qualities. At the time, it was utilized to treat soil to prevent the spread of *Phylloxera* spp. in grapevines (*Vitis vinifera*). Since chloropicrin has nematicidal properties, it was also utilized to treat nematodes (trichloro-nitromethane). Although nematicidal activity in a synthetic chemical was discovered as a result of the use of carbon disulfide as a soil fumigant in the second half of the nineteenth century, research on the use of nematicides stalled until surplus nerve gas (chloropicrin) became widely accessible after World War I (Brown 1987).

The decade between 1940 and 1950 was profoundly important for the Science of Nematology. Nematicidal properties were discovered for three chemicals: methyl bromide (bromomethane), D-D mixture (1,3-dichloropropene, 1,2-dichloropropane), and EDB (1,2-dibromoethane; commonly called ethylene dibromide). Beginning in the early 1940s, methyl bromide was once the most widely used nematicide in the USA. The Montreal Protocol classified methyl bromide as a Class I ozone-depleting agent, and as a result, the manufacturing and use of the chemical were banned internationally in industrialized nations in 2005 (Fourie et al. 2017). In the 1940s, the discovery that D-D mixture controlled the soil populations of PPNs and led to substantial increases in crop yield provided a great impetus to the development of other nematicides, as well as the development of the science of nematology. Both D-D and EDB, unlike previously identified fumigants, were primarily nematicidal chemicals, easier to apply, and more economical to use. In later years, the 1,3-dichloropropene (1,3-D) component of the D-D mixture was shown to represent approximately 98% of the nematicidal activity of the mixture (Youngson and Goring 1970). As a result of these findings and the presence of 1,2-dichloropropane (1,2-D) contaminants in drinking water, 1,2-D was subsequently removed from the mixture. Subsequently, other halogenated hydrocarbons and other volatile compounds were developed as nematicidal soil fumigants. Metham (sodium N-methyl dithiocarbamate dihydrate) was the last fumigant nematicide introduced and has been shown to control various nematodes, weeds, some fungi, and insects. This material hydrolyzes in soil to form a volatile gas, methyl isothiocyanate (MIT), which is a toxic entity. Metham can be applied as a drench, in irrigation water, or injected into the soil (Rich et al. 2009).

Despite the efficiency of fumigants in nematode control, the application difficulties associated with the high costs and high environmental risk of these extremely toxic products resulted in the reduction of their use (Starr et al. 2007). In the 1960s, a new generation of nematicides was introduced, carbamates and organophosphates, that served as contact nematicides, devoid of fumigant activity. The discovery of the nematicidal activity of this chemical led to the testing and development of several other non-fumigant nematicides such as aldicarb, carbofuran, ethoprop, and fenamiphos which are still in production today.

CHEMICAL GROUP OF NEMATICIDES

Nematicides can be divided into groups based on their chemical constitution (for example, isothiocyanates, carbamates, and organophosphates), mode of action (for example, acetylcholinesterase inhibitors), and method of use (e.g., fumigant, non-fumigant) as shown in Fig. 1. The majority of the data used to explain nematicide precise activity in nematodes comes from studies of their recognized effects in insects and mammals, even though there is a wealth of evidence to support the effectiveness of nematicides. The way an active component of a nematicide affects nematodes is known as its mode of action. The mode of action of nematicides can be described at a variety of physiological levels, including morphological alterations, impacted cellular components or biochemical processes, and molecular activity sites.

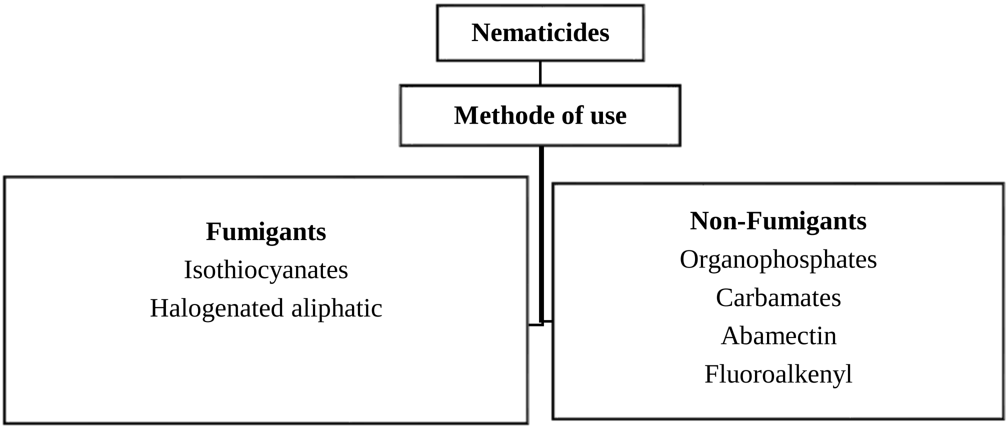

Fig. 1. Groups of nematicides

Fumigant nematicides.

Fumigant nematicides can be divided into two different chemical groups: (1) the halogenated aliphatic hydrocarbons, i.e., ethylene dibromide (EDB), 1,3-dichloropropene mixtures (1,3-D and D-D), l,2-dibromo-3-chloropropane (DBCP) and methyl bromide, and (2) the methyl isothiocyanate (MIT) liberators, i.e., metam sodium, dazomet, and MIT mixtures.

Fumigant nematicides, including methyl bromide, methyl iodide, chloropicrin, 1,3-dichloropene, dimethyl dibromide, and metam sodium and potassium, are formulated in liquids that, when exposed to air, quickly evaporate and flow through open air holes in soil as a gas. They commonly sink deep into the soil due to the detachment of their molecules in the vapor phase, and when exposed to the water in the soil, they disintegrate into chemicals that enter the nematode's cuticle and quickly react with proteins, amino acids, and oxidases to cause metabolic dysfunctions (Galbieri and Belot 2016).

Impact of fumigant nematicides in PPNs.

Broad-spectrum fumigant nematicides do not require ingestion to work because they penetrate the nematode's body wall directly. Since they are drenched in nematicide-containing bodily fluids once they have entered the nematode body cavity, they have an impact on many internal organs (Noling 1997a). Halogenated hydrocarbons have the principal function of acting as alkylating agents. These fumigants are believed to have an immediate impact on respiration and protein synthesis metabolic processes. Protein sulfhydryl groups are more susceptible to methyl bromide-induced methylation (Butler and Rodriguez 1996). According to studies done on nematodes, EDB oxidized Fe^{2+} centers and alkylated proteins in the cytochrome-mediated electron transport chain, limit nematode respiration (Wright 1981).

Metam sodium (Vapam) is a highly soluble compound that activates in water. Decomposition proceeds swiftly in water. Dazomet and sodium N-methyldithiocarbamate, often known as metam sodium, break down in soil to produce methyl isothiocyanate. Cyanide, once within the worm, blocks the use of oxygen, which is likely delivered by oxygen-transporting globins, and so stops respiration. The enzymatic, neurological, and respiratory systems are all affected by a secondary by-product (MITC) that enters through the worm body wall and forms when water is present (Noling 1997a). Unlike D-D, *Rotylenchulus uniformis* eggs and juveniles are equally sensitive to dazomet, although there is limited data on the susceptibility of various nematode species or stages to any of these fumigants (Seinhorst 1973). Beyond a minimal threshold lethal concentration of a fumigant, the susceptibility of a nematode to a fumigant has long been known to be proportional to the product of the concentration of the fumigant and the duration of exposure, i.e., the concentration-time product. Giannakou and Karpouzas (2003) stated that “fumigant nematicides (1,3-dichloro propene, metham sodium) were more effective in the control of root-knot nematodes than non-fumigant nematicides (fenamiphos, cadusafos, and oxamyl)”.

D-D and its nematicidal component 1,3-D are presumably very effective in the field against nematodes of all species, whereas EDB is generally not recommended for cyst nematodes and DBCP is not recommended for *Trichodorus* spp. reported to be inadequate for control (Van Berkum and Hoestra 1979). For EDB, this may be partly due to its relatively low volatility and hence low activity at low temperatures. They showed that juveniles of *Aphelenchus avenae* were able to tolerate EDB exposure for longer periods than juveniles of *Tylenchulus semipenetrans* or *Meloidogyne javanica*, and juvenile stages of *A. avenae* were generally more susceptible to EDB than the adults.

Non-fumigant nematicides.

Non-fumigant nematicides are nonvolatile poisonous chemicals that can be applied previous to planting, at planting, or after planting through soil drenching, drip irrigation, or scattering onto the crop leafage to reduce population consistency of nematodes and cover crops from damage. From the 1960s, new classes of nematicidal products were developed: organophosphates and carbamates, classified as non-fumigant nematicides.

A major advantage of organophosphates and carbamates is their low persistence as toxic molecules compared to chlorinated hydrocarbon nematicides (Galbieri and Belot 2016). These substances can either be created as liquids, granules, or both. An organophosphorus insecticide called Caudusafos is manufactured as granules (Rugby 200 CS) and liquid (Apache 100 GR). These nematicides are more potent than fumigants even at low concentrations because they have a systemic effect on PPNs. They are highly harmful to mammals and insects despite having little to no phytotoxic action, which causes environmental issues (Jr 1985).

Nematicides are classified into one of two categories: systemic (which kills nematodes after they feed from plant roots) or contact (which kills nematodes in soil by direct exposure). Nematicide non-fumigant compounds spread throughout the soil after being applied by the water in the soil. Non-fumigants effectiveness is independent of soil temperature, unlike fumigant nematicides. The main organismal mode of action may be temporary paralysis, interference with host seeking, suppression of hatching, or disruption of some other process because contact nematicide concentration in agricultural soils after application is typically not high enough to kill nematodes. Inhibition of hatching occurred at concentrations not expected to take place in the field, but the three carbamates aldicarb, carbofuran, and cloethocarb hindered *H. schachtii* juvenile mobility at concentrations of nematicide that occur in field circumstances (Hartwig and Sikora 1991). Because soil is a heterogeneous combination, it is doubtful that a chemical nematicide, even a fumigant, will entirely eliminate a nematode population. Furthermore, contact nematicides are applied in amounts too low to result in instantaneous death. However, the restriction on movement and penetration is typically significant enough to prevent damage to the economy. For perennials or crops with prolonged growth seasons, the reduction in nematode populations may not always last long enough to eliminate the requirement for post-plant reapplication of nematicides. However, higher initial nematicide application rates are usually not economical and may be linked to increasing hazards to the environment or other factors.

As soon as systemic nematicides are applied to plant foliage or the soil, they may be quickly absorbed and disseminated inside the root tissues of plants. Plant uptake, translocation, and ultimate nematicide content in roots are all influenced by a wide range of variables. If there are significant leaching losses, pesticides that are very soluble and mobile in soil may limit the ability of plants to concentrate systemic nematicides in roots. The size of the entire plant or root system also seems to be significant. Systemic nematicides (Temik, Vydate, Nemacur) appear to have toxic qualities that are more protective than directly harmful to the worm. Instead of killing nematodes as the term implies, systemic nematicides that are absorbed and translocated into roots appear to only prevent them from eating, render them temporarily inactive, or drive them away from the roots and their surroundings. In these cases, death occurs as a result of disorientation and starvation.

Impact of non-fumigant nematicides in PPNs.

Non-fumigant nematicides can also directly pierce nematodes body walls. Contrary to fumigants, these substances offer little to no protection against bacterial or fungal infections, but depending on the nematicide employed, they may be insecticidal. The acetylcholinesterase inhibitory properties of the carbamates (Temik, Vydate) and organophosphates (Mocap, Nemacur) used as pesticides prevent normal nerve impulse transmission in insect central nervous systems. This has a history of causing strange behavior, paralysis, and even death. Information on non-fumigant nematicides indicates that nematodes more basic nervous systems may also be impacted. These substances are not typically regarded as real nematicides since they are not as harmful to nematodes as they are to insects. Instead of being killed, nematode death frequently results from a "narcotic" impact and behavioral change. Nematode behavior and development in soil are predominantly impacted by nerve impulse disruption, which can ultimately be fatal at high concentrations over an extended period. For instance, root penetration, nutrition, mobility in the soil, and body movement are all affected. There may also be impaired development inside plant tissues, delayed egg hatch, and molting. The observed decreases in nematode population increase after non-fumigant nematicide treatment are principally attributable to decreased worm infection, development, and reproduction in the plant (Vale and Lotti 2015).

Organophosphate and carbamate nematicides have a more reliable mode of action than fumigant nematicides. It is accepted that the latter compounds act principally by inhibition of acetylcholinesterase at cholinergic synapses in the nematode nervous system (Le Patourel and Wright 1974), which is the same mode of action as in vertebrates and arthropods (Corbett 1974). Suppression of general cholinesterase activity by both organophosphate and carbamate pesticides has been conducted in vitro using extracts from several nematode species (Hart and Lee, 1966; Knowles and Casida 1966) and cholinesterase activity in the region of the nematode nerve ring inhibited by the organophosphate pesticide phorate (Rohde 1960) and by the carbamate oxamyl (Hogger et al. 1978).

NEW SYNTHETIC NEMATICIDES

The newly developed synthetic nematicides listed in Table 1 have distinct effect and regulatory requirements concerning human and environmental safety compared to their predecessors. The registration of these new nematicides is largely based on their behavior in soil, including factors such as leaching potential, soil persistence, selectivity, effects on beneficial soil organisms, degradation, and metabolism pathways (Desaeger et al. 2020). Most old-generation nematicides have been banned due to environmental pollution and human toxicity. Out of the 20 key nematicides used in the twentieth century, only 4 (fluopyram, oxamyl, fenamiphos, and ethoprop) are approved for use in the European Union, and only 3 (fluopyram, oxamyl, and 1,3-D) are unrestricted for use in the United States. Additionally, the new generation nematicide, iprodione, has been banned in Europe due to its potential carcinogenicity and high toxicity to aquatic animals (Jiang et al. 2024).

Despite these challenges, several new compounds with very promising efficacy have been developed and released in recent years or are in the process of being registered for use, namely fluensulfone, fluopyram, and fluazaindolizine (Jiang et al. 2024). Overall, all the 3-F nematicides have much lower water solubility, but longer soil half-lives than oxamyl. These nematicides exhibit a significantly safer toxicity profile compared to older classes of nematicides, such as fumigants, organophosphates, carbamates (Table 1). Despite their shared 3-F group, these nematicides differ considerably in their chemical and physical properties, as well as in their modes of action.

Fluensulfone, developed by ADAMA and first registered in the USA in 2014 for certain vegetables, is a nematicides with a unique mode of action as a fatty acid beta-oxidation inhibitor, although this mode of action remains unpublished. Unlike older generations of nematicides, fluensulfone poses significantly lower toxicity risks to humans and non-target organisms. Research by Kearn et al. (2017) demonstrated that when second-stage juveniles (J2) of *Globodera pallida* were exposed to fluensulfone, they exhibited increased lipid content, cell viability loss, and tissue degeneration, and these symptoms were not observed in adult of *C. elegans* (Kearn et al. 2017). In soil, fluensulfone degrades into three primary metabolites: methyl sulfone, thiazole sulfonic acid, and butene sulfonic acid, with the latter two being the major metabolites absorbed by plants (APVMA, 2015). Fluensulfone exhibits specific nematicidal activity, which makes it especially effective against *Meloidogyne* species. It is currently registered for use on various crops, including tomato, cucumber, bell pepper, squash, potato, cabbage, broccoli, melon, lettuce, strawberry, and turf, targeting important nematode genera and species such as *Belonolaimus*, *Globodera*, *Hoplolaimus*, *Meloidogyne*, and *Pratylenchus*, depending on the crop and country of registration.

Fluopyram developed by Bayer CropScience (Fought et al. 2009) and introduced in 2009, a member of pyridinyl-ethyl-benzamide group, was initially developed as a fungicide against several fungal pathogens, such as *Botrytis*, *Sclerotinia*, *Erysiphe*, and *Pyrenophora* spp. Its nematicidal activity was discovered later. Fluopyram is regarded as the first SDHI (Succinate Dehydrogenase Inhibitor) nematicide, specifically targeting complex II of the mitochondrial respiratory chain. This inhibition results in a rapid depletion of energy within nematode cells, ultimately causing nematode death (Chen et al. 2020). Fluopyram is recognized for its fast action and high potency as a nematicide. Unlike other 3-F nematicides, it has an exceptionally long soil half-life, lasting up to 746 days. Fluopyram can be considered a "true nematicide," as it causes irreversible immobilization and leads to nematode death even after brief exposure at relatively low concentrations (Oka and Saroya 2019).

Fluazaindolizine, the most recent of the new chemical nematicides, was expected to be registered in 2020 (Lahm et al., 2017). Similar to fluensulfone, fluazaindolizine specifically targets nematodes, with no reported fungicidal or insecticidal activity. It belongs to the carboxamide class, and while its mode of action remains unknown, it is distinct from that of carbamates, organophosphates, or any other known nematicides (Lahm et al., 2017). A study examining the behavior of fluazaindolizine in a tomato field analyzed the metabolites present in soil and plants, revealing that fluazaindolizine is a readily degradable nematicide (Chen et al 2018).

Additionally, other new-generation nematicides, such as spirotetramat, a tetramic acid derivative and systemic insecticide, exhibit distinctive translocation properties, moving throughout the entire vascular system of plants. This nematicide functions by inhibiting acetyl-CoA carboxylase activity, altering lipid storage and fatty acid composition, and disrupting surface coat synthesis in *Caenorhabditis elegans* (Gutbrod et al. 2018). Unlike many other nematicides, spirotetramat is a relatively recent systemic option that can be applied through foliar spraying. Similarly, tioxazafen, a systemic nematicide from the oxadiazole class, acts by disrupting the ribosomal activity of PPNs. This nematicide is primarily used as a seed treatment, offering consistent broad-spectrum control of nematodes in crops such as corn, soy, and cotton (Slomczynska et al. 2015).

Table 1. Characteristics of new synthetic nematicides and their mode of action

Chemical name	First use	Product type	Mode of action	Signal words
Spirotetramat	2008	Tetramic acid	ACC inhibitor	Caution
Dimethyl disulfide	2010	Fumigant	Multi-site	Danger
Allyl ITC	2013	Fumigant	Multi-site	Danger
Fluopyram	2013	Benzamide	SDHI inhibition	Caution
Fluensulfone	2014	Thizaole	Beta oxidation inhibitor	Caution
Tioxazafen	2017	Oxadiazole	Disrupts ribosomal activity	Caution
Fluazindolizine	2020	Carboxamide	unknown	Caution

Note: ACC = acetyl-CoA carboxylase; SDHI = succinate dehydrogenase inhibition (Desaeger et al. 2020).

EFFECT OF NEMATICIDES IN HUMAN AND ENVIRONMENT

Nematicides are intended to control nematodes, but some pesticides can have harmful impacts on ecosystems and human health. Acute and chronic poisoning can result from ingesting, inhaling, or coming into touch with pesticide residues on the skin. Such toxicity levels depend on nematicide types, entrance points, dose, metabolism, accumulation, and other factors. Chronic toxicity is caused by repeated or long-term exposure and occurs over a longer length of time than acute toxicity, which is caused by short-term exposure and occurs in a relatively short amount of time. It mostly interferes with the body's metabolic and systemic processes. The pesticide's chemical component interferes with neurological activity. Additionally, it harms the immunological and endocrine systems (Wesseling et al. 1997).

Human safety.

Exposure during application.

Nematicides are extremely hazardous substances with very low lethal concentrations (LC_{50}, the level at which 50% of animals die). This is crucial for workers who operate application equipment and are at danger of chemical exposure during application. Some of the non-fumigant nematicides have liquid formulations that are emulsifiable concentrates. Therefore, only trained users who take appropriate safety measures should utilize them. This might not always be the case if operators cannot comprehend the product labels instructions or if fundamental educational levels are low. Another concern that pesticide residue monitoring may not be able to adequately prevent is the use of nematicides to crops too soon before harvest.

Remnants in foodstuffs.

Pesticides can also reach humans through the ingestion of contaminated food and water. Some pesticide applications do, however, leave residues in the crop that is harvested. The process for approving pesticides includes provisions for the problem of residues in foods and animal feeds. Maximum residue levels (MRLs) are created to track proper pesticide use, and potential residual levels should be toxicologically acceptable. Recent European legislation has undergone significant revisions, imposing stricter regulations on the use of pesticides in agricultural crops, with a strong emphasis on environmental safety as well as human and animal health. The level of chemical residues in food products varies depending on the type of nematicide used. For instance, the MRL for dazomet is 20 µg/kg, while oxamyl is permitted on crops like tomatoes, peppers, eggplants, melons, tobacco, cucumbers, and squash, with an MRL of 10 µg/kg (PPDB 2021). Additionally, in the United States, the MRLs for certain foods, such as tomatoes and cucumbers, are set at 1.0 ppm and 0.6 ppm, respectively (EPA 2016).

Nematicides in the environment.

To guarantee that the control measures chosen can be efficient, ecologically safe, and cost-effective, a well-informed management plan is required. Groundwater contamination is one of the more serious environmental issues sometimes connected to the use of nematicides. Unfortunately, this is rarely the case because the majority of pesticides are general-purpose and may kill organisms that are beneficial to the ecosystem or harmless. The majority of pesticides are thought to poison the environment, with just around 0.1% of them reaching the intended target organisms (Carriger et al. 2006). The repeated use of persistent and non-biodegradable pesticides has contaminated multiple components of water, air and soil ecosystem.

Soil and groundwater.

If nematicides are left in the topsoil, where microbial activity is highest, they will eventually decompose. Nematicides may have a longer persistence after being washed through the upper soil layers or their breakdown products. Nematicides must break down into innocuous substances to stop sticking around in the environment. Nematicides must, however, be sufficiently persistent to successfully manage the target nematode population. Once applied to the soil, there could be direct losses by volatilization to the atmosphere. The majority of the nematicides that is applied, ends up in the soil where it may be physically lost from the soil through leaching or surface runoff or destroyed by microbial or chemical activity. When nematicides are broken down to produce a source of carbon or energy, soil bacteria play a crucial role in the process. However, efficacy can be compromised if the breakdown happens too quickly. Nematicides degrade more quickly in soils that are warm, damp, and alkaline because these are the ideal environmental conditions for microbial activity. Reduced persistence may be the outcome of applying nematicide to the same soil repeatedly. This has been seen for several carbamates and is known as rapid or increased microbial decomposition (Karpouzas and Giannakou 2002). Nematicides may enter groundwater if they are lost from the soil by leaching or surface runoff, both of which are extremely uncommon. Aldicarb and 1,3-D are two nematicides for which this has been recorded (Karpouzas and Giannakou 2002).

Similar to how contact nematicides travel away from their application area, it depends on adsorption onto organic material. Aldicarb and oxamyl are effective in soils with a wide range of organic matter concentrations, whereas ethoprop and fenamiphos are less efficient in soils with high levels of organic matter. Fenamiphos and aldicarb's sulfoxide and sulfone derivatives are more mobile in soils than their parent nematicides and have the potential to contaminate groundwater more easily (Loffredo et al. 1991). The carbamate group is hydrolyzed in oxamyl, not aldicarb. At 10 separate sites, the conversion of oxamyl into harmless oximes was typically accompanied by an increase in pH, warmth, and moisture (Haydock et al. 2012).

Non-target organisms.

Pesticides impact on creatures other than their intended targets has drawn attention and concern on a global scale for many years. Pesticide use has been linked to negative outcomes for non-target arthropods, according to multiple reports (Ware 1980). Unfortunately, pesticides have a particularly negative impact on natural insect adversaries including parasitoids and predators (Vickerman 1988).

Nematicides are usually non-selective pesticides, and their application will generally have an impact on organisms that are not intended targets. The majority of nematicides significantly change soil flora and fauna due to their broad-spectrum actions. Because of the uncontrolled use of nematicides in agricultural systems, the population of soil arthropods is also severely disrupted along with that of their antagonists. When non-target creatures are exposed to lethal or harmful doses of the active ingredient directly by ingestion, contact, or exposure, this has the most visible consequences.

The carbamates oxamyl, aldicarb, and carbofuran (or their metabolites) and the organophosphates fenamiphos, ethoprophos, and cadusafos are all extremely harmful to fish and birds, except oxamyl and ethoprophos, which are only moderately toxic. Van Straalen and Van Rijn (1998) outlined the work that showed carbofuran to be lethal to a wide range of soil organisms including collembola, carabid beetles and earthworms. Stenersen (1979) studied the effect of several chemicals on earthworms and reported that aldicarb was the most toxic, whereas oxamyl was not toxic to any of the species tested. This indicates that even though chemicals may belong to the same family and have related modes of action, they may not all have the same effects on the environment.

Furthermore, a chemical can affect a non-target creature without coming into direct touch with it or exposing it to it directly. For instance, birds may ingest spilled granules and become directly exposed, but they may also consume contaminated earthworms and become indirectly exposed to the chemical. In contrast to non-fumigants, some fumigant nematicides present a further risk to species that are not the intended targets: exposure to the chemical's gaseous state. In this regard, the toxicity classification can be based on inhalation tests on mammals; from these, the EC classification for methyl bromide and chloropicrin is "toxic," while the classification for 1,3-D is "damaging." But, there is no inhalation classification for metam sodium and dazomet. However, dazomet and metam sodium do present significant harm to aquatic creatures and the aquatic environment.

In comparison to untreated soils, potato fields that had received long-term aldicarb treatment had fewer bacterial genera and species, fewer populations of *Rhizobacteria* that promote plant growth, and more total bacterial biomass (Sturz and Kimpinski 1999). Nematicides have the ability to significantly change the structure of nematode communities in soils. For instance, *Helicotylenchus* was replaced by *Pratylenchus* as the main PPNs after pasture soil had been treated with methyl bromide (Yeates and Van Der Meulen 1996).

When considering the impact of new-generation nematicides on non-target microorganisms, it is important to note that the manufacturer's recommended application rate for fluopyram is quite low, ranging from 197 to 207 g ha^{-1}, and not exceeding 494 g ha^{-1} per year. This dosage is roughly one-tenth of that recommended for fluensulfone. Such low application rates may help preserve soil microbial ecosystems, including free-living nematodes and beneficial fungi like mycorrhiza, while also minimizing residue levels in crops. However, higher doses might be more effective in controlling PPNs. Research has shown that fluensulfone, while effectively managing *Meloidogyne* spp., did not significantly alter the diversity of free-living nematode populations and had only a minimal suppressive effect on these non-target organisms (Kawanobe et al., 2019).

Fluensulfone, unlike older nematicides, is significantly less toxic to humans and non-target organisms, with an acute LD_{50} of 671 mg/kg in rats, making it considerably safer than older nematicides. However, it is relatively toxic to aquatic organisms, with an EC_{50} of 0.35 mg/L for *Daphnia magna* after 48 h and about 0.04 mg/L for certain green algae species after 72 h. Consequently, its use should be restricted near aquatic environments to prevent harm (APVMA 2019).

Ozone depletion.

Since methyl bromide is poisonous and nonselective when utilized, it also affects species that are not intended targets. This can involve employees working at the application location. The Montréal Protocol on Substances that Deplete the Ozone Layer (1992) establishes a timeline for industrialized and developing countries to reduce and eventually stop using methyl bromide because it is likewise categorized as an ozone-depleting substance. There will be some exceptions for "essential" purposes beyond the phase-out date in 2005, when usage should end in industrialized countries, and after 2015 in developing countries. Penkett et al. (1985) measured concentrations of methyl bromide in the atmosphere and found concentrations were higher in the Northern than in the Southern Hemisphere. These authors speculated that human activity was the primary cause of emissions of methyl bromide into the atmosphere.

CHALLENGES

Since nematodes cannot be completely eradicated, the objective is to control their population and bring it down to harmful levels. Planting resistant varieties, rotating crops, integrating soil amendments, and using pesticides are a few common management techniques. Nematode control cannot be accomplished solely by diagnosing the nematodes and using the proper nematicide. Numerous nematicides made by chemicals are costly, carcinogenic, and hazardous to people, animals, and the environment. Additionally, they are known to eventually degrade the quality of the soil and contaminate the groundwater. Moreover, unfavorable climatic conditions can make the applied nematicide ineffective against nematodes (Jones et al. 2013). Nematicides are a distinctly 20th-century phenomenon since they were first discovered, developed and widely used during that century. With nematicide technology, as in most scientific advances, a large body of knowledge was created which eventually not only showed the many advantages but also the limitations and disadvantages of the technology. As a result, several nematicides were canceled or use restrictions placed upon them to mitigate problems not recognized when they first were used. Wright (1981) alluded to problems of nematicides and many of his comments were prophetic of future events.

Aside from the high toxicity, another problem of nematicide use is the decreased nematicidal activity after repeated applications of the same or a related nematicide to the same field (Davis et al. 1993, Ou et al. 1994, Suett and Jukes 1988). This phenomenon was initially thought to be caused by the development of nematode populations that were resistant to the nematicides. However, in actuality, the decrease in nematicidal activity was found to be caused by the development of soil microorganisms that can use the nematicides as a substrate for their energy generation, termed enhanced or accelerated biodegradation (Cabrera 2010). Nematicides applied to such soil can be degraded more rapidly than in soil with no history of the same nematicide application (Smelt et al., 1987).

With the new nematicides being more selective, and potentially used more frequently, resistance may be more likely to occur. For instance, SDHI compounds like fluopyram, having long soil persistence and similar mode-of-action towards fungi and nematodes, are likely to put significant selection pressure on target nematodes. It is also well-known that many of the older organophosphate and carbamate nematicides can lose efficacy over time due to accelerated degradation in the soil caused by microbial adaptation (Smelt et al., 1987; Johnson, 1998).

Present uses.

Despite product cancellations and use restrictions, and the lesser specter of enhanced biodegradation, nematicides are widely used, particularly in developed countries and on higher value crops. For example, over 80% of flue-cured tobacco hectares in Canada, the USA, and Zimbabwe receive annual nematicide applications (Rich et al. 1989). In Florida, almost 100% of the 16,000 ha of fresh market tomatoes are also treated with multipurpose fumigants, with nematode control as a major element in choosing this treatment (Noling 1997b). Production of these high-value crops is very risky economically, so many growers have used the most effective broad-spectrum fumigants possible to limit even small losses. Multipurpose fumigants have given this assurance to growers in the past and were readily adopted since other management techniques were less reliable.

For many vegetable crops, for example, plant resistance is not available, is limited to only a few potential nematode pests, may be limited by soil temperature, and/or is subject to resistance-breaking biotypes. Crop rotation with less profitable crops often is not an economical option or if possible, only shortened rotations are practical. Thus, agriculture continues to need and demand nematicides.

Farmer's knowledge about nematodes.

A colloquium on tropical nematology was held in 1994 at the 22nd International Symposium of the European Society of Nematologists in Ghent, Belgium. Tropical nematology's shortcomings and needs were summed up as (i) a lack of fundamental knowledge, (ii) a dearth of tropical nematologists engaged in research, (iii) a lack of collaboration, (iv) a communication gap between temperate and tropical nematologists, and (v) a lack of awareness among farmers, agricultural scientists, extension specialists, and decision-makers (Prot and Kermarrec 1995). Nematode awareness by farmers is important not only to implement nematode management strategies, which require that farmers can recognize and understand the pathogen problem in their fields. Farmers in southern Europe have considered soil chemical fumigation, as the most effective method for controlling root knot nematode diseases in intensive horticultural crops, since the efficacy of other nematode control methods has not proven consistent enough when high RKN soil infestations occur (Talavera et al., 2024; Greco et al., 2020). When nematode management was applied, the farmers were able to recognize the effect of the treatment but did not attribute it to the control of the nematodes because of their microscopic size (Speijer et al. 2001).

Proper selection of nematicides.

Managing nematodes in tropical and subtropical environments is a challenge. There are a few effective control measures, and these must be used under conditions in which they will work. For effective management of nematodes, the critical steps are (1) accurate diagnosis, and (2) proper selection of the most effective and environmentally benign control method should be applied.

Nematicide treatment rates required for effective nematode control can be influenced by nematicide adsorption to soil organic matter, treated soil volume (which is determined by soil type), and soil moisture content. For instance, studies have shown that nematicide treatments are typically more effective once crop debris has started to degrade since there is less nematicide adsorption. Larger treatment rates for fumigant nematicides and perhaps non-fumigant nematicides may be required for efficient nematode control because of the "sink" effects of organic matter in soil pH (Noling 1997a).

As indicated, the mobility of a nematicide relies upon, especially upon its affinity for soil organic matter and the physical characteristics of the soil to which it is applied. In sandy soils for example, both Temik and Vydate are weakly adsorbed to organic matter and consequently potentially very mobile in soil, whereas Nemacur and Mocap are greater strongly absorbed and much less mobile. It is identified at this factor that many nematicides are degraded into byproducts that are toxic to nematodes and which bind and leach in the soil in a different way than the guardian nematicide. For example, Nemacur is degraded into two toxically energetic components in plant life and soil, and these metabolites may also be greater cellular than the mother or father compound itself although still less mobile than Vydate and perchance Temik. So, one of a kind nematicides must be applied in the discipline primarily based on the nature, stage, and type of nematode, kind of soil, and active compound in the nematicide, and through considering these matters proper management of nematode can be done (Noling 1997a).

Alternative of nematicides to control nematodes.

We have already discussed nematicides and their effects on human health, soil, and water, as well as non-target creatures. Because nematodes cannot be eradicated, the goal is to regulate their population and keep it below dangerous levels. Planting resistant crop varieties, rotating crops, integrating soil amendments, and spraying pesticides are all common management techniques. Solarization of the soil may be feasible in some instances. Because there are so few and their nematode resistance is particular, the application of resistant plant cultivars is limited. Because nematode resistance is species- and race-specific, precise identification of the nematode species and race is required before selecting the appropriate cultivar (Schmitt and Sipes 1998)

Thoden et al. (2011) highlighted the application of various organic amendments that have proven successful in mitigating the effects of PPNs in various crop plants. The amendments, such as slurries and their organic acids, had the potential to accumulate/form high concentrations of nematicidal compounds and were able to create anaerobic conditions to directly suppress the PPN population. To control the root-lesion nematode *Pratylenchus penetrans*, Korthals et al. (2014) reported using eight soil health treatments (anaerobic soil disinfestation, biofumigation, chitin, compost, grass-clover, marigold, a physical technique, and a combination of marigold, compost, and chitin). Regarding their positive impact on the physical and chemical qualities of soil, all of the treatments were shown to be superior substitutes for chemical treatments. The overall beneficial effect of organic improvement agents is a result of their role in strengthening the population of free-living nematodes, insects, and bacteria. These organisms go on to play a significant role in promoting plant growth, nutrient supply, and mineralization, making plants resistant to PPN infections. Fallow soil deprives PPNs of a living host, which over time reduces their populations. Green manuring, tilling under a crop that grows rapidly and produces a lot of biomasses that adds organic matter and, depending on the green manure crop used, may add substances that repel or kill nematodes.

In the EU, the following extracts are registered as active ingredients: garlic extract, clove oil, a mixture of oils based on thymol and geraniol, and azadirachtin whose result have been found comprehensive in various research. The persistence of the product is about 14 days; therefore, after the first treatment, the product should be applied at 2-week intervals (Andres 2012). The formulations are effective against *Meloidogyne* spp., *Tylenchus* spp., *Trichodorus* spp., *Longidorus* spp., *Pratylenchus* spp., *Xiphinema* spp. and the cyst nematodes *Globodera* spp. and *Heterodera* spp. (Andres 2012, Jardim 2020). The commercial product is a natural formulation based on clove oil extracted from *Eugenia caryophillata* with high nematostatic and nematicidal action (Meyer 2008).

Another nonchemical approach to controlling nematodes is organic control using other organisms towards the pest organism. An excessive level of herbal organic manipulation is basically existing in the soil. Most organisms determined to be concerned with nematode suppression are nematophagous fungi (e.g *Pochonia chlamydosporia, Hirsutella rhossiliensis*, *Dactylella oviparasitica*) and bacteria (e.g *Pasteuria penetrans*) that parasitize their nematode hosts. Microbes that compete for nutrients, produce toxins, or result in host resistance, such as some rhizosphere microorganisms (e.g *Pseudomonas* spp., *Agrobacterium radiobacter, Bacillus subtilis*) may also decrease nematode harm, however, can also no longer furnish the long-term manipulate of nematode populations associated with suppressive soils. It is generally difficult to apply biological control agents for the administration of PPNs, and the majority of empirical studies has produced contradictory outcomes. Some products, such as *Paecilomyces* spp., *P. penetrans*, and *Trichoderma* spp., have been commercialized, but some may also be used practically in nematode treatment. The steps for commercialization include resolving the most impressive isolates, producing inoculum, and developing a technique for the microbial agents. The application of organic control retailers must be taken into consideration within the context of various management approaches, notably, their interaction with cultural control methods since biological control is not a substitute for chemical control (Atkinson 1992; Lee 2002).

There is always a need for new nematicidal compound formulations, but there are not any that are close to commercial development at the moment. Microbial-derived avermectins, which are effective anthelmintics, have been produced for veterinary use. The efficiency of compounds against PPNs is well-known; however, their complexity prevents them from being used as effective soil treatments. An ideal nematicide should be highly effective against all PPNs at a low cost and dose, while being non-toxic to non-targets, including crops. Additionally, it should be easily applicable and safe for users, consumers, and the environment. Furthermore, new application methods, such as seed treatment, can reduce the application dose and cost, as well as protect plants at a crucial stage of development, while safeguarding the environment from nematicide pollution. The three nematicides probably have different modes of action, and this can be an advantage in nematode management. Additionally, we must keep in mind that managing nematodes is a difficult task that requires more than just using nematicide; instead, an integrated management approach must be used for cost-effective and environmentally sustainable nematode management.

CONCLUSION

PPNs are becoming more of a problem, and proper nematode management is required for efficient crop production. There are various types of chemical nematicides, each with its mode of action and effect on nematode physiological levels such as morphological changes, affected cellular components or biochemical processes, and molecular activity sites. Because nematicides are harmful to human health, soil, groundwater, and non-target organisms, proper nematicide selection and application methods are critical. Other control methods must be integrated for improved control. Although chemical control began with more harmful effects, new compounds that are less aggressive and more specific for PPNs have been developed, making this tool safer for the producer, the consumer, and the environment. Because nematodes cannot be eliminated, the goal is to manage their population, reducing their numbers to dangerous levels. The first step in effective nematode management is an accurate diagnosis, followed by the proper selection of the most effective and environmentally friendly control method. Crop rotation, cover crops, and other alternative method can be combined into a cultural method.

RESUME

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Les nématodes parasites des plantes sont de minuscules animaux vermiformes pseudocoelomates, non segmentés, bilatéralement symétriques qui attaquent les plantes. Les nématicides sont des substances synthétisées chimiquement qui tuent ou nuisent aux nématodes. Entre 1940 et 1950, trois produits chimiques aux propriétés nématicides ont été découverts: le bromure de méthyle (bromométhane), le mélange D-D et l'EDB (1,2-dibromoéthane, sous forme de dibromure d'éthylène) qui étaient des fumigants. Lorsque des composés fumigants sont appliqués au sol, un gaz se déplace à travers les espaces ouverts entre les particules du sol ou dans le film d'eau qui entoure les particules du sol. Les fumigants diminuent considérablement la respiration des nématodes en oxydant les centres Fe^{2+} et les protéines alkylées dans la chaîne de transport d'électrons médiée par le cytochrome. Malgré l'efficacité des fumigants contre les nématodes, leur utilisation a été réduite en raison du risque environnemental élevé de ces produits. Une nouvelle génération de nématicides a été introduite: les carbamates et les organophosphates qui ont servi comme nématicides de contact, ce qui a conduit à tester et à développer d'autres nématicides non fumigants tels que l'aldicarbe, le carbofuran, l'éthoprop et le fénamiphos. Les propriétés inhibitrices de l'acétylcholinestérase des carbamates et des organophosphorés empêchent la transmission normale de l'influx nerveux dans le système nerveux des nématodes. Les nématicides sont généralement des pesticides non sélectifs et leur utilisation a un impact sur les organismes non ciblés, l'homme et l'environnement. Puisque les nématicides sont toxiques pour l'homme, le sol, les eaux souterraines et les organismes non ciblés, une sélection et une application prudentes des nématicides sont essentielles. De nouveaux composés moins agressifs et plus spécifiques aux nématodes phytoparasites ont été développés, les rendant plus sûrs pour le producteur, le consommateur et l'environnement. La rotation des cultures, les cultures de couverture, la fumure organique, l'utilisation de variétés résistantes et d'autres méthodes doivent être intégrées aux nématicides pour une efficacité élevée.

Mots clés: Empoisonnement, nématicides, nématodes phytoparasites, oorganophosphorés, sécurité humaine

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ملخص

تيواري، سريجان. 2024. تأثير المبيدات النيماتودية على النيماتودا الطفيلية النباتية: التحديات والسلامة البيئية. Tunisian Journal of Plant Protection 19 (2): 101-120.

النيماتودا الطفيلية النباتية هي حيوانات دودية صغيرة، شبه جوفية، غير مجزأة، ثنائية التناظر تهاجم النباتات. المبيدات النيماتودية هي مواد مصنعة كيميائيًا تقتل أو تضر بالنيماتودا. بين عامي 1940 و1950، تم اكتشاف ثلاث مواد كيميائية ذات خصائص قاتلة للنيماتودا: بروميد الميثيل (بروموميثان)، وخليط D-D، و EDB (1،2- ثنائي بروموميثان؛ مثل ثنائي بروميد الإيثيلين) والتي كانت مبيدات مبخِّرة. عندما يتم تطبيق مبيدات مبخّرة على التربة، يتحرك الغاز عبر المساحات المفتوحة بين جزيئات التربة أو إلى طبقة الماء التي تحيط بجزيئات التربة. تقلل المبيدات المبخّرة بشكل كبير من تنفس النيماتودا عن طريق أكسدة مراكز Fe^{2+} والبروتينات المؤلكلة في سلسلة نقل الإلكترونات بوساطة السيتوكروم. على الرغم من فعالية المبيدات المبخّرة على النيماتودا، انخفض استخدامها بسبب المخاطر البيئية العالية لهذه المواد. تم تطوير جيل جديد من المبيدات النيماتودية: الكارباماتات والفوسفاتات العضوية التي تعمل كمبيدات نيماتودية ملامِسة، مما أدى إلى

اختبار وتطوير مبيدات نيماتودية غير مبخّرة أخرى مثل الألديكارب والكاربوفوران والإيثوبروب والفيناميفوس. تمنع خصائص الكارباماتات والفوسفاتات العضوية المثبطة لأستيل كولينستريز انتقال النبضات العصبية الطبيعية في الجهاز العصبي للنيماتودا. المبيدات النيماتودية هي مبيدات غير انتقائية بشكل عام، واستخدامها يؤثر على الكائنات غير المستهدفة والإنسان والبيئة. وبما أن المبيدات النيماتودية سامة للإنسان والتربة والمياه الجوفية والكائنات غير المستهدفة، فإن اختيار هذه المبيدات وتطبيقها بحذر أمر حيوي. تم تطوير مبيدات نيماتودية جديدة أقل عدوانية وأكثر تخصصا للنيماتودا الطفيلية النباتية، مما يجعلها أكثر أمانًا للمنتج والمستهلك والبيئة. يجب دمج تناوب المحاصيل ومحاصيل التغطية والتسميد العضوي واستخدام الأصناف المقاومة وطرق أخرى في استعمال المبيدات النيماتودية لزيادة فعالية المكافحة.

كلمات مفتاحية: تسمم، سلامة الإنسان، فوسفاتات عضوية، مبيدات نيماتودية، نيماتودا طفيلية نباتية

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Plant Protection Events

Report

on

National Citrus Course

Hammamet, Tunisia, April 15-19, 2024

General presentation

The National Citrus Course (NCC), organized annually by the Technical Center of Citrus (CTA) for the past 13 years, has become a key event for professionals in the citrus-growing sector. This gathering serves as an essential platform for practitioners, researchers, and engineers to exchange knowledge and ideas

The program fosters collaboration among agronomists, researchers, and growers to enhance the implementation of Integrated Pest Management (IPM) practices in Tunisia's citrus sector.

Participants

Attendees represented governmental, semi-governmental, and private organizations operating within the citrus industry.

Program

The NCC featured diverse sessions and discussions on citrus cultivation, focusing on the adoption of best practices and innovations. The training spanned four days of theoretical learning and one day of fieldwork, covering all disciplines related to the citrus crop, including production, protection, sanitation, economics, and innovation.

Citrus protection was a central theme of the program, with two days dedicated to high-quality presentations. The crop protection themes addressed the following key aspects:

- Importance of Resistant Rootstocks in Citrus
- Biological control practices
- Major fungal diseases and management
- Management of citrus pests
- Good phytosanitary practices
- Strategies to reduce pesticides in citrus production
- Precision agriculture and pesticide application
- Post-harvest practices for disease prevention

Presentations were delivered by the CTA engineers and teacher-researchers from INAT and ISACh-M, showcasing the latest developments in the sector from both research and practical perspectives. Following each presentation, productive exchanges between participants and speakers enabled attendees to broaden and deepen their knowledge.

Conclusion

At the conclusion of this national course, participants and speakers emphasized its importance in updating knowledge and facilitating the exchange of ideas among professionals. They also highlighted the practical aspects of the course, which effectively complemented the theoretical knowledge provided.

Report of *Prof. Hanène Chaabane-Boujnah*
INAT, University of Carthage, Tunis
Tunisia

Report

on

Workshop on "Prevention of AMR and Integrated Pest Management and Presentation of the Good Agricultural Practices" (AMR- MPTF UNJP/TUN/047/UNJ)

Hammamet, Tunisia, December 10-11, 2024

Context

The management of crop pests and diseases is essential to ensure the sustainability and safety of agricultural production. The adoption of Integrated Pest Management (IPM), a sustainable approach, helps reduce pesticide use while ensuring environmental protection.

In Tunisia, several initiatives have been implemented to reduce the use of pesticides, including significant efforts to align national legislation with international and regional regulations. On November 15, 2010, a new regulatory text was promulgated featuring an updated approval process and introducing new regulatory requirements and measures for pesticide, resulting in a remarkable reduction in the number of approved active substances. Additionally, the financial contribution related to approval operations was halved for biological products (N O G, 03 June 2011).

Furthermore, Tunisia has signed and ratified most international conventions on the management of risks associated with these chemicals, including the Rotterdam Convention on the "Prior Informed Consent" procedure for certain hazardous chemicals and pesticides subject to international trade.

Other important measures have been taken to encourage the reduction and/or rationalization of pesticide use to promote sustainable agriculture through the adoption of IPM approach and other alternative pest control methods (biocontrol products such as pheromones, biological control, biotechnical means, resistant varieties, plant extracts, algae-based extracts, microorganism-based suspensions, etc.).

The use of antimicrobials in phytosanitary practices aims to control fungal and bacterial infections threatening crops. However, their intensive and sometimes inappropriate use promotes the development of microbial resistance. This resistance occurs when pathogens adapt to antimicrobial treatments, rendering them ineffective, which can lead to a significant agricultural loss. Moreover, antimicrobials applied to crops can end up in the environment, where they contribute to the selection of resistant microorganisms. This situation poses a risk to human and animal health, as these resistant organisms can spread and limit therapeutic options, particularly for humans. Therefore, the careful and responsible management of these products in agriculture is crucial to limit the emergence and spread of antimicrobial resistance.

A better understanding of the mode of action of these products, the crops where their use is increasing, the dangers they pose to the environment and human and animal health, and finally, how to prevent and limit them, is essential to ensure safe and compliant products.

Aims of the project

The UNJP/TUN/047/UNJ project "Supporting the Implementation of the National Action Plan on Antimicrobial Resistance (AMR) in Tunisia by Adopting the 'One Health' Approach" supports the National Action Plan (NAP) developed in 2019 on AMR, focusing primarily on awareness, surveillance, and prevention of infections related to human health, animal and plant health, and food safety.

Objectives of the workshop

The national Workshop on "Prevention of AMR and Integrated Pest Management and presentation of the Good Agricultural Practices" co organized by **FAO** and **General Directorate of Plant Health and Control of Agricultural Inputs (DG/SVCIA)** aimed to establish a harmonized and sustainable approach for managing AMR in crops in Tunisia. The workshop focused on enhancing the knowledge and skills of national stakeholders on the responsible use of fungicides and other antimicrobials while integrating the principles of IPM. By promoting proactive and informed risk management of antimicrobials, the event sought to facilitate the effective implementation of best practices within an IPM approach adapted to local specificities.

Target public and workshop outcomes

The workshop brought together officials responsible for plant protection from various central and regional services of the Ministry of Agriculture, Water Resources, and Fisheries, along with representatives from stakeholders' institutions, over two intensive days.

During the two working days, the focus was on the main crops in Tunisia that use antimicrobials (Potato, Cereals and Grapes), addressing the associated risks of resistance, and exploring effective management strategies. Through group work sessions, participants discussed guidelines for best practices to mitigate AMR risks, ensuring these recommendations are practical and actionable for field application.

Report of *Essia Limam, DG.SVCIA-FAO, Tunis Tunisia*

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Photo of the cover page: Striped mealybug on coffee plant (Courtesy *Bouzid Nasraoui*)

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