Ovicidal and Larvicidal Effects of Selected Plant-Based Biopesticides on *Tuta absoluta* (Lepidoptera: Gelechiidae)[1]

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Abstract The tomato leafminer, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), is a worldwide invasive pest of tomatoes (*Solanum lycopersicum* L.) that reached West Africa in 2010. Synthetic insecticides remain the most widely used method of control, but several biological alternatives are being developed. In this work, we evaluated nine biopesticides available on the West African market for their ability to control *T. absoluta*. Using standard leaf or egg dip bioassay methodology, we compared both the ovicidal and the larvicidal activity of these biopesticides at various concentrations of active ingredients. We found that, for each biopesticide tested, the larval lethal concentrations (LC) (8.2–41.14 ml/L) to be lower than those necessary to stop egg hatching (26.7–409.7 ml/L). Two products (Bangr-Kièta [BK]; Bangr-Pougo [BP], formulated in powder), both based on *Azadirachta indica* A. Jussieu fruit and leaf extracts and *Khaya senegalensis* (Desrousseaux) A. Jussieu bark extract, showed high efficacy in reducing egg hatchability at their recommended doses, with a calculated control failure likelihood (CFL) reaching 0%. These two products, together with a third one (BP) based on *Mitracarpus scaber* Zuccarini and *K. senegalensis* extracts, also showed the strongest larvicidal effects (CFL = 0%). All other tested biological insecticides showed significant efficiency but were found to be less effective at their recommended doses. Because the leafminer has developed resistance to most of the synthetic insecticide available on the market, we recommend that West African tomato producers are encouraged to use the most efficient biological products available.

Key Words: bioinsecticide, *Azadirachta indica*, *Khaya senegalensis,* control failure likelihood

The tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is a worldwide invasive insect pest that has colonized Europe, Africa, Asia, and the Caribbean during the last two decades (Biondi et al. 2018, Son et al. 2017, Verheggen and Fontus 2019). It feeds mainly on the Solanaceae, with a preference for tomatoes (*Solanum lycopersicum* L.) (Sawadogo et al. 2022), in which the larvae cause production losses of up to 100% when no control measures are applied (Sawadogo et al. 2020a). Various methods of control have been evaluated in the past, including

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physical (stump removal, pruning, trapping, physical barriers), biological (predators, parasitoids), semiochemical (mass trapping with light and pheromones, mating disruption), genetic (resistant or tolerant varieties), and agricultural strategies (Chidege et al. 2018, Ferracini et al. 2019, Han et al. 2016, Jallow et al. 2020, Larbat et al. 2016, Ouardi et al. 2012, Sawadogo et al. 2021, Sohrabi et al. 2016, Zarei et al. 2019). However, chemical control with synthetic pesticides remains the most widely used, especially in the newly invaded areas (Han et al. 2019, Sawadogo et al. 2020b). However, because of repeated applications and misuses, some leafminer populations have developed resistance to several active ingredients, making their control even more difficult (Guedes et al. 2019, Sawadogo et al. 2020b).

Biological pesticides formulated from microbial agents, chemicals of biological origin, and RNA interference (RNAi) technology have already proven to be effective against *T. absoluta*, while being less harmful to beneficials (Mansour and Biondi 2021). Different biological products based on plant extracts also have been evaluated to control the tomato leafminer, including essential oils of Zingiberaceae, Asteraceae, Cupressaceae, and Asteraceae (Alam et al. 2017, Campolo et al. 2017, Chegini et al. 2018, Umpiérrez et al. 2017), methanolic extracts from Euphorbiaceae, Nitrariaceae, and Urticaceae (Ait Taadaouit et al. 2012), and emulsifiable formulations of Meliaceae and Rutaceae (Abd El-Ghany et al. 2018, Campolo et al. 2017). Several products are available on the West African market, even though their efficiency has barely been evaluated following proper methodology. In this work, we evaluated and compared nine plant-based insecticides available in the West African market for their ability to control *T. absoluta* eggs and larvae.

Materials and Methods

Insects. Approximately 1,200 larvae were collected between February and April 2020 in open tomato fields located in the proximity of Bobo Dioulasso (Burkina Faso) and transported to the laboratory. Insects were placed in rearing cages (80 $\times$ 40 $\times$ 40 cm) and fed tomato plants (cv. Rossol) grown without pesticides. After adult emergence, new plants were introduced in the cages and used for oviposition. After hatching, larvae were fed until their second stage (L2) when they were used for larval sensitivity tests. All rearing and bioassays were conducted at temperatures of 28 $\pm$ 3°C, relative humidity (RH) of 55 $\pm$ 15%, and under a 12:12 h photoperiod.

Bioinsecticides. All plant-based insecticides available on local markets in Burkina Faso were purchased and included in the assays (Table 1). These biopesticides were purchased from companies or producer associations based in Ouagadougou. None provided information on their labels as to ovicidal or larvicidal activity against *T. absoluta*.

Ovicidal activity. We first evaluated the ability of the different bioinsecticides to prevent *T. absoluta* eggs from hatching. Eggs were collected from the rearing cages less than 12 h after adult oviposition, keeping them attached to the tomato leaves. As per Ekesi et al. (2002), the tomato leaves with leafminer eggs were soaked for 3 s in the test solution containing 0.02% (v/v) Triton X100. A series of concentrations of each biopesticide was tested (Table 2), with 35 eggs tested for each concentration $\times$ biopesticide combination. After soaking, the tomato leaves with eggs were air-dried for 30 min under laboratory conditions and then placed in Petri

Table 1. Biopesticides tested in laboratory bioassays.

Manufacturer	Trade Name	Active Ingredient	Recommended Dose (ml/L)
Bioprotect*	Neem oil (HN)	*A. indica* extracts	11.5
	Piol	*Capsicum annuum* L., *Allium cepa* L., *A. sativum* L., *A. indica* extracts	13.61
	Limosain	*Pinus* sp. extracts + Natural flavors, Mn, B, MaO, D-limonene	6.8
	Biopoder	*A. indica*, *Brassica* sp., *C. annuum*, *A. sativum*, *Mentha* sp. extracts	12.6
	Neem oil (HNN^{+})	*A. indica* extracts	7.56
	Neem oil (HNN^{++})	*A. indica* extracts	7.56
Action Research Group Zems-Taaba of ADESVK**	Bangr-pougo (BP)	*M. scaber* and *K. senegalensis* extracts	200
	Bangr-kièta (BK)	Extracts of fruit and leaf of *A. indica* and extracts of bark of *K. senegalensis*	200
	Bangr-pougo (BP) formulated in powder	Extracts of fruit and leaf of *A. indica* and extracts bark of *K. senegalensis* (powder)	10 (g/l)

* Bioprotect: formulator and distributor of biopesticide certified BIO SPG and ECOCERT based in Ouagadougou, Burkina Faso.

** Action Research Group Zems-Taaba of ADESVK (Association pour le Développement Economique et Sociale du Village de Koala): Group of agricultural producers and traditional practitioners based in Sanba (Ouagadougou).

Table 2. Ovicidal effects of nine biopesticides on *T. absoluta*.

Bioinsecticides	N	Number and Range of Concn. (ml/L) Tested	LC_{50} (ml/L)	95% CL	LC_{80} (ml/L)	95% CL	Slope ± SE	χ^2	Control Failure Likelihood (%)
HN	105	3 (5–53)	26.7	20.5–46.8	43.3	31.8–88.2	0.05 ± 0.02	0.34	71.2
Piol	140	4 (25–104)	67.3	59.1–83.4	91.6	77.8–127.7	0.04 ± 0.01	0.46	95.6
Biopoder	175	5 (10–173)	106.2	88.9–173	163.7	129.9–482.8	0.02 ± 0.01	0.11	89.4
Limosain	210	6 (100–680)	409.7	344.5–518.2	587.6	488.6–794.4	0.01 ± 0.00	0.23	96.9
HNN^{+}	140	4 (10–91)	61.6	52.5–76.9	91.6	76.5–123.3	0.03 ± 0.01	0.38	92.5
HNN^{++}	175	5 (5–85)	49.8	40–60.3	79.1	66.7–110.9	0.03 ± 0.01	0.45	86.2
BP*	210	6 (70–480)	303.6	253.5–418.6	449.2	359.9–690.3	0.01 ± 0.00	0.03	63.7
BK	175	5 (11–100)	61.3	47.7–71	92.9	81.6–116.7	0.03 ± 0.01	0.1	0
BP powder	210	6 (10–150)	93.7	79.6–107.3	141.8	125.6–168.5	0.02 ± 0.00	0.24	0

* LC_{50} and LC_{80} expressed as milligrams per liter.

dishes containing slightly moistened filter paper which was then covered and sealed with parafilm. Distilled water containing 0.02% Triton X100 was used as the control. Observations with a binocular magnifying glass were conducted each morning and evening to monitor egg hatching.

Larvicidal activity. The Insecticide Resistance Action Committee 022 methodology (www.irac-online.org) was followed to evaluate the larvicidal activity of the nine biopesticides. A series of concentrations of each biopesticide was tested using 32 L2 larvae for each concentration (Table 3). Tomato leaves were soaked for 3 s in a given concentration of each of the nine bioinsecticides with 0.02% Triton X100, after which they were air-dried for 30 min in ambient laboratory conditions. A single larva was then placed on a treated tomato leaf in a Petri dish containing slightly moistened filter paper. The control was treated with distilled water + 0.02% Triton X100. Larval mortality was assessed 72 h later. Any larva failing to display coordinated movement after three consecutive stimulations with a pair of forceps was considered dead.

Statistical analysis. Mortality rates were corrected using Abbott's formula for natural mortality (Abbott 1925). A probit dose-mortality response analysis was performed on the corrected data to determine the lethal concentrations for each biopesticide tested. The 95% confidence limit (CL) was used to determine statistical significance between lethal concentrations of the biopesticides. Overlap of 95% CLs of the lethal concentrations of products indicated the lack of significant difference between the products, while nonoverlap of the 95% CLs indicated statistical difference. In addition, based on the manufacturers' recommended doses, we used the formula of Guedes (2017) to calculate control failure likelihood (CFL), which is the probability that a given product used at the manufacturer recommended dose fails in controlling the pest population: CFL = 100 − (achieved mortality [%] × 100)/expected mortality (typically >80%). For all biopesticides (Tables 2, 3), the values (responses) predicted by the log (dose)–probit (mortality) model did not differ significantly from the values observed in the bioassays; thus, the probit model was found suitable for concentration/response analyses.

Results

Ovicidal activity. Bangr-kièta (BK) and Bangr-pougo (BP) powder significantly reduced egg hatch, with calculated CFLs calculated of 0% for both products (Table 2). Huile de Neem (neem oil) (HN) and BP not formulated as a powder had low ovicidal activity with CFL levels of 71% and 64%, respectively. The remaining five bioinsecticides had no ovicidal effect, with CFLs >85%.

Larvicidal activity. BP not formulated as a powder, BK, and BP powder, at the manufacturers' recommended doses, eliminated >80% of *T. absoluta* larvae and exhibited the highest larval toxicity of the nine biopesticides tested in our bioassays (Table 3). The CFLs of each of these products was 0%. Larval mortality resulting from treatment with HN, HNN^{++}, or Biopoder did not differ significantly, as indicated by overlapping 95% CLs of their respective LC_{50} values. The CFLs of these three products were 30%, 40%, and 47.5%, respectively. Also based on 95% CLs of their respective LC_{50} values, larval mortality following exposure to Limosain, Piol, and

Table 3. Larvicidal effects of biopesticides on L2 *T. absoluta* larvae.

Bioinsecticides	N	Number and Range of Concn. (ml/L) Tested	LC_{50} (ml/L)	95% CL	LC_{80} (ml/L)	95% CL	Slope ± SE	χ^2	Control Failure Likelihood (%)
HN	320	10 (3.3–40)	9.14	0.84–14.101	24.23	18.69–37.07	0.06 ± 0.008	18.37	30
Piol	288	9 (6.7–64)	29.42	24.06–34.72	57.56	49.45–72.09	0.03 ± 0.005	10.72	60
Biopoder	288	9 (9–80)	22.77	11.76–31.52	71.5	58.49–95.75	0.017 ± 0.003	3.24	47.5
Limosain	384	12 (6.7–80)	25.66	13.39–35.53	69.24	54.22–107.41	0.19 ± 0.003	15.52	55
HNN^{+}	352	11 (3.3–50)	28.18	22.07–36.39	48.2	39.2–66.79	0.42 ± 0.005	21.44	76.2
HNN^{++}	352	11 (3.3–50)	8.95	4.45–12.68	31.87	26.07–42.20	0.037 ± 0.006	13.28	40
BP	320	10 (6.7–80)	41.14	34.12–48.75	81.59	70.04–101.004	0.021 ± 0.003	10.72	0
BK	320	10 (6.7–60)	35.99	31.97–40.30	58.10	52.32–66.32	0.038 ± 0.004	11.86	0
BP powder*	320	10 (10.6–69)	8.20	−3.47–15.21	38.04	32.38–45.83	0.028 ± 0.005	4.9	0

* LC_{50} and LC_{80} are expressed as milligrams per liter.

HNN^{+} did not differ significantly and were the least effective of the nine biopesticides tested (e.g., CFLs range, 55%–76.2%).

Comparison of ovicidal and larvicidal activities. Of the nine products assayed, BK and BP powder performed best as both ovicidal and larvicidal agents against *T. absoluta*, based on their CFL values of 0% (Tables 2, 3). BP not formulated as a powder also was an effective larvicide with a CFL of 0% (Table 3). We also found that the LC_{50} and LC_{80} values calculated for each of the biopesticides were higher against *T. absoluta* eggs than L2 larvae (Tables 2, 3); thus, indicating that a higher concentration of these products is required to kill eggs than larvae.

Discussion

The nine biopesticides we tested were formulated from several botanical sources, each of which had been previously reported to exhibit insecticidal activity (Chaieb et al. 2018, Chermenskaya et al. 2010, Doumbia et al. 2014, Fragoso et al. 2021, Kim et al. 2003, Mercier et al. 2009, Mobki et al. 2014, Murovhi et al. 2020, Ramdani et al. 2020, Sinzogan et al. 2006, Tavares et al. 2021). Furthermore, combinations of plant extracts are expected to demonstrate synergistic effects allowing for improved efficacy and control of a wide range of insects.

From our laboratory bioassays of the nine products, we learned that BK and BP powder were the most effective ovicides against *T. absoluta* eggs, while BK, BP, and BP powder were the most effective larvicides against *T. absoluta* L2 larvae. BK and BP powder are derived from extracts of the fruits and leaves of *Azadirachta indica* A. Jussieu combined with extracts from the bark of *Khaya senegalensis* (Desrousseaux) A. Jussieu. BP is derived from extracts of *Mitracarpus scaber* Zuccarini and *K. senegalensis*.

Azadirachtin, derived from *A. indica*, is a triterpenoid that inhibits feeding, oviposition (Arnó and Gabarra 2011), and growth regulation (Schlüter et al. 1985). It is one of the main biological products currently used in leafminer control (Biondi et al. 2018, Guedes et al. 2019). It reportedly has little effect on leafminer beneficials, including adults of *Macrolophus pygmaeus* Rambur, *Trichogramma cacoeciae* Marchal, and the nematode *Steinernema feltiae* Filipjev (Amizadeh et al. 2019, Arnó and Gabarra 2011, Cherif et al. 2018). It also exhibits a similar level of efficacy as indoxacarb, metaflumizone, and abamectin (Nannini et al. 2011). However, some populations (e.g., Urla) of *T. absoluta* are not very sensitive to this product, resulting in the need for additional management tactics to control the leafminer pest (Yalçin et al. 2015).

Extracts from the bark of *K. senegalensis* are popular in traditional medicine in Africa (Drijfhout and Morgan 2010). Several triterpenoids also have been identified from the bark extracts and have proven to be potent antifeedants against *Spodoptera littoralis* (Boisduval) in bioassays. Extracts of *M. scaber* are also used in traditional medicine in West Africa and have been demonstrated to have insecticidal properties against several insect pests, including mosquito larvae (Abdullahi et al. 2011) and beetle adults in stored products (Doumbia et al. 2014).

The LC_{50}s of each of the nine bioinsecticides tested were higher against the *T. absoluta* eggs than the LC_{50}s of the same products against the L2 larvae (Tables 2, 3). The egg shell apparently provides some protection for the developing embryo from topically-applied toxins. Furthermore, a biocidal product with antifeedant activity would target actively feeding stages of the pest insect. Thus, our results corroborate the conclusions of Campolo et al. (2017) and Chegini et al. (2018) that higher doses of the agent are required to prevent egg hatch than to kill larvae. While other botanical extracts (essential oils of *Elettaria cardamomum* (L.) Maton and *Zataria multiflora* Boiss.) have shown ovicidal effects (Chegini et al. 2018), these oils likely had fumigant properties.

Only two biopesticides (BK and BP powder) led to an acceptable ovicidal effect. For the other seven biopesticides, a higher dose than the ones recommended are likely be required to achieve acceptable management of *T. absoluta* eggs on tomatoes. Further complicating this approach is that *T. absoluta* females lay most of their eggs on the underside of leaves (Cherif et al. 2013) and are, therefore, difficult to reach with topically applied products (Koppel et al. 2011). Control with these biopesticides should, therefore, be initiated as soon as the larvae hatch, as at this time the insect could receive the product either by contact, inhalation, or ingestion.

Even though all nine biopesticides tested herein reportedly are larvicidal at the manufacturers' recommended doses, only BK, BP and BP powder demonstrated acceptable CFL levels in our bioassay. Increasing the recommended doses might allow for improved efficacy. Several other biopesticides in the form of essential oils have shown larvicidal effects on *T. absoluta*. For example, the essential oil of *Thymus capitatus* (L.) Hoffmanns. & Link and *Tetraclinis articulata* Vahl at 0.2 ml/L induced 80% mortality of all larval instars and 100% mortality of first-instar larvae after 1.5 h of exposure (Alam et al. 2017). Citrus peel essential oil in foliar application yielded similar results after 72 h with a concentration of 40 g/L (Campolo et al. 2017). Under greenhouse conditions, Prev-am® essential oil (made of orange oil, salt borax, and biodegradable surfactants; ORO AGRI International Ltd, Groningen, The Netherlands), as a foliar treatment, gave comparable results to lambda-cyhalothrin for the reduction of the *T. absoluta* population. This reduction is even higher when applied at half the recommended dose (10% or 0.024 g/L) in combination with the generalist predator *Nesidiocoris tenuis* Reuter (Soares et al. 2019). These and other aspects of managing *T. absoluta* on tomatoes using botanical extracts require further study with additional life stages and in field environments as well as the laboratory or greenhouse. However, our results serve as an important foundation for these additional studies.

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References Cited

Abbott, W.S. 1925. A method of computing the effectiveness of an insecticide. J. Econ. Entomol. 18: 265–267.

Abd El-Ghany, N.M., A.S. Abdel-Razek, K. Djelouah and A. Moussa. 2018. Efficacy of bio-rational insecticides against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on tomatoes. Biosci. Res. 15: 28–40.

Abdullahi, K., M.G. Abubakar, R.A. Umar, M.S. Gwarzo, M. Muhammad and H.M. Ibrahim. 2011. Studies on the larvicidal efficacy of aqueous extracts of *Strigia hermenthica* (Delite) Benth and *Mitracarpus scaber* (Zucc.) on *Culex qunquefasciatus* (Culicidae) mosquito larvae. J. Med. Plt. Res. 5: 5321–5322.

Ait Taadaouit, N., M. Hsaine, A. Rochdi, A. Nilahyane and R. Bouharroud. 2012. Effet des extraits végétaux méthanoliques de certaines plantes marocaines sur *Tuta absoluta* (Lepidoptera, Gelechiidae). European and Mediterranean Plant Protection Organization (EPPO) Bull. 42: 275–280.

Alam, S.B., M.E.A. Dib, N. Djabou, B. Tabti, G.N. Benyelles, J. Costa and A. Muselli. 2017. Essential oils as biocides for the control of fungal infections and devastating pest (*Tuta absoluta*) of tomato (*Lycopersicon esculentum* Mill.). Chem. Biodivers. 14: 1–9.

Amizadeh, M., M. Jalil, H. Gholamreza and N. Ghasem. 2019. Interaction between the entomopathogenic nematode, *Steinernema feltiae* and selected chemical insecticides for management of the tomato leafminer, *Tuta absoluta*. BioContr. 64: 709–721.

Arnó, J. and R. Gabarra. 2011. Side effects of selected insecticides on the *Tuta absoluta* (Lepidoptera: Gelechiidae) predators *Macrolophus pygmaeus* and *Nesidiocoris tenuis* (Hemiptera: Miridae). J. Pest Sci. 84: 513–520.

Biondi, A., R.N.C. Guedes, F. Wan and N. Desneux. 2018. Ecology, worldwide spread, and management of the invasive South American tomato pinworm, *Tuta absoluta*: past, present, and future. Annu. Rev. Entomol. 63: 239–258.

Campolo, O., A. Cherif, M. Ricupero, G. Siscaro, K. Grissa-Lebdi, A. Russo, L.M. Cucci, P.D. Pietro, C. Satriano, N. Desneux, A. Biondi, L. Zappalà and V. Palmeri. 2017. Citrus peel essential oil nanoformulations to control the tomato borer, *Tuta absoluta*: chemical properties and biological activity. Sci. Rep. 7 : 13036.

Chaieb, I., K. Zarrad, R. Sellam, W. Tayeb, A.B. Hammouda, A. Laarif and S. Bouhachem. 2018. Chemical composition and aphicidal potential of *Citrus aurantium* peel essential oils. Entomol. Gen. 37: 63–75.

Chegini, S.G., H. Abbasipour, J. Karimi and A. Askarianzadeh. 2018. Toxicity of *Shirazi thyme*, *Zataria multiflora* essential oil to the tomato leaf miner, *Tuta absoluta* (Lepidoptera: Gelechiidae). Int. J. Trop. Insect Sci. 38: 340–347.

Cherif, A., R. Mansour and K. Grissa-lebdi. 2013. Biological aspects of tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) in conditions of Northeastern Tunisia: possible implications for pest management. Environ. Exp. Biol. 11: 179–184.

Cherif, A., O. Ichaoui, S. Barhoumi-attia and K. Grissa-lebdi. 2018. Life-stage-dependent side effects of selected insecticides on *Trichogramma cacoeciae* (Marchal) (Hymenoptera: Trichogrammatidae) under laboratory conditions. Phytoparasitica 46: 105–113.

Chermenskaya, T.D., E.A. Stepanycheva, A.V. Shchenikova and A.S. Chakaeva. 2010. Insectoacaricidal and deterrent activities of extracts of Kyrgyzstan plants against three agricultural pests. Ind. Crops Prod. 32: 157–163.

Chidege, M., N. Hassan, J. Abisgold and S. Al-Zaidi. 2018. Sustainable approach in bio-rational management of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Tanzania. Acta Hort. 1225: 451–455.

Doumbia, M., K. Yoboue, D.K. Kra, J. Klimaszewski, K.E. Kwadjo, B.G. Douan and M. Dagnogo. 2014. Testing of insecticidal extract from *Mitracarpus scaber* Zucc. (Rubiale: Rubiaceae) against four stored food products insect pests in Ivory Coast. Int. J. Entomol. Res. 02: 81–86.

Drijfhout, F.P. and E.D. Morgan. 2010. Terrestrial natural products as antifeedants, Pp. 457–501. *In* Hung-Wen Lui and L. Mander (eds.), Comprehensive natural products II. Elsevier Ltd., Amsterdam, The Netherlands.

Ekesi, S., R.S. Adamu and N.K. Maniania. 2002. Ovicidal activity of entomopathogenic hyphomycetes to the legume pod borer, *Maruca vitrata* and the pod sucking bug, *Clavigralla tomentosicollis*. Crop Prot. 21: 589–595.

Ferracini, C., V.H.P. Bueno, M.L. Dindo, B.L. Ingegno, M.G. Luna, N.G.S. Gervassio, N.E. Sánchez, S. Gaetano, J.C.V. Lenteren, L. Zappalà and L. Tavella. 2019. Natural enemies of *Tuta absoluta* in the Mediterranean basin, Europe and South America. Biocontr. Sci. Technol. 29: 578–609.

Fragoso, D.F.M., A.C. Túler, D. Pratissoli, J.R. Carvalho, W.R. Valbon, V.T.D. Queiroz, P.F. Pinheiro, A.V. Costa and R.C.O.F. Bueno. 2021. Biological activity of plant extracts on the small tomato borer *Neoleucinodes elegantalis*, an important pest in the neotropical region. Crop Prot. 145: 1–8.

Guedes, R.N.C. 2017. Insecticide resistance, control failure likelihood and the first law of geography. Pest Manag. Sci. 73: 479–484.

Guedes, R.N.C., E. Roditakis, M.R. Campos, K. Haddi, P. Bielza, H.A.A. Siqueira, A. Tsagkarakou, J. Vontas and R. Nauen. 2019. Insecticide resistance in the tomato pinworm *Tuta absoluta:* patterns, spread, mechanisms, management and outlook. J. Pest Sci. 92: 1329–1342.

Han, P., N. Desneux, C. Becker, R. Larbat, J. Le Bot, S. Adamowicz, J. Zhangand and A.V. Lavoir. 2019. Bottom–up effects of irrigation, fertilization and plant resistance on *Tuta absoluta*: implications for Integrated Pest Management. J. Pest Sci. 92: 1359–1370.

Han, P., N. Desneux, T. Michel, J. Le Bot, A. Seassau, E. Wajnberg, E. Amiens-Desneux and A.V. Lavoir. 2016. Does plant cultivar difference modify the bottom-up effects of resource limitation on plant-insect herbivore interactions? J. Chem. Ecol. 42: 1293–1303.

Jallow, M.F.A., A.A. Dahab, M.S. Albaho, V.Y. Devi, J. Jacob and O. Al-Saeed. 2020. Efficacy of mating disruption compared with chemical insecticides for controlling *Tuta absoluta* (Lepidoptera: Gelechiidae) in Kuwait. Appl. Entomol. Zool. 55: 213–221.

Kim, S.I., J.Y. Roh, D.H. Kim, H.S. Lee and Y.J. Ahn. 2003. Insecticidal activities of aromatic plant extracts and essential oils against *Sitophilus oryzae* and *Callosobruchus chinensis*. J. Stored Prod. Res. 39: 293–303.

Koppel, A.A.L., D.A. Herbert, T.P. Kuhar and S. Malone. 2011. Efficacy of selected insecticides against eggs of *Euschistus servus* and *Acrosternum hilare* (Hemiptera: Pentatomidae) and the egg parasitoid *Telenomus podisi* (Hymenoptera: Scelionidae). J. Econ. Entomol. 104: 137–142.

Larbat, R., S. Adamowicz, C. Robin, P. Han, N. Desneux and J.L. Bot. 2016. Interrelated responses of tomato plants and the leaf miner *Tuta absoluta* to nitrogen supply. Plant Biol. 18: 495–504.

Mansour, R. and A. Biondi. 2021. Releasing natural enemies and applying microbial and botanical pesticides for managing *Tuta absoluta* in the Mena region. Phytoparasitica 49:179–194.

Mercier, B., J. Prost and M. Prost. 2009. The essential oil of turpentine and its major volatile fraction (α- and β-pinenes): A review. Int. J. Occup. Med. Environ. Health 22: 331–342.

Mobki, M., S.A. Safavi, M.H. Safaralizadeh and O. Panahi. 2014. Toxicity and repellency of garlic (*Allium sativum* L.) extract grown in Iran against *Tribolium castaneum* (Herbst) larvae and adults. Arch. Phytopathol. Plant Prot. 47: 59–68.

Murovhi, J., M.M. Phophi and P. Mafongoya. 2020. Efficacy of plant materials in controlling aphids on okra (*Abelmoschus esculentus* L. Moench) in Limpopo province of South Africa. Agron. 10: 1–11.

Nannini, M., F. Foddi, G. Murgia, R. Pisci and F. Sanna. 2011. Insecticide efficacy trials for management of the tomato borer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), a new tomato pest in Sardinia (Italy). Acta Hortic. 917: 47–54.

Ouardi, K., M. Chouibani, M.A. Rahel and M. El Akel. 2012. Stratégie nationale de lutte contre la mineuse de la tomate *Tuta absoluta* Meyrick. European and Mediterranean Plant Protection Organization (EPPO) Bull. 42: 281–290.

Ramdani, C., R. Bouharroud, M. Sbaghi, A. Mesfioui and M. El Bouhssini. 2020. Field and laboratory evaluations of different botanical insecticides for the control of *Dactylopius opuntiae* (Cockerell) on cactus pear in Morocco. Int. J. Trop. Insect Sci. 41:1623–1632.

Sawadogo, M.W., I. Somda, S. Nacro, A. Legrève and F. Verheggen. 2020a. Cinq années d' invasion: Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso. Tropicultura 38: 1–14.

Sawadogo, M.W., I. Somda, S. Nacro, A. Legrève and F.J. Verheggen. 2020b. Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso. Physiol. Entomol. 45: 147–153.

Sawadogo, M.W., R.A. Dabire, B.R. Ahissou, S. Bonzi, I. Somda, S. Nacro, C. Martin, A. Legrève and F.J. Verheggen. 2021. Comparison of life history traits and oviposition site preferences of *Tuta absoluta* for twelve common tomato varieties in Burkina Faso. Physiol. Entomol. 47: 1–7.

Sawadogo, W.M., B.R. Ahissou, I. Somda, S. Nacro, A. Legrève and F.J. Verheggen. 2022. Identification of alternative hosts of the tomato leafminer in West Africa. African Entomol. (In Press).

Schlüter, U., H.J. Bidmon and S. Grewe. 1985. Azadirachtin affects growth and endocrine events in larvae of the tobacco hornworm, *Manduca sexta*. J. Insect Physiol. 31: 773–777.

Sinzogan, A.A.C., D.K. Kossou, P. Atachi and A. Van Huis. 2006. Participatory evaluation of synthetic and botanical pesticide mixtures for cotton bollworm control. Int. J. Trop. Insect Sci. 26: 246–255.

Soares, M.A., M.R. Campos, L.C. Passos, G.A. Carvalho, M.M. Haro, A.V. Lavoir, A. Biondi, L. Zappalà and N. Desneux. 2019. Botanical insecticide and natural enemies: a potential combination for pest management against *Tuta absoluta*. J. Pest Sci. 92: 1433–1443.

Sohrabi, F., H. Nooryazdan and B. Gharati. 2016. Evaluation of ten tomato cultivars for resistance against tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under field infestation conditions. Entomol. Gen. 36: 163–175.

Son, D., S. Bonzi, I. Somda, T. Bawin, S. Boukraa, F. Verheggen, F. Francis, A. Legrève and B. Schiffers. 2017. First record of *Tuta absoluta* (Meyrick , 1917) (Lepidoptera: Gelechiidae) in Burkina Faso. African Entomol. 25: 259–263.

Tavares, W.R., D.C.M. Barreto and A.M.L. Seca. 2021. Aqueous and ethanolic plant extracts as data and practical reality. Plants 10: 1–30.

Umpiérrez, M.L., J. Paullier, M. Porrini, M. Garrido, E. Santos and C. Rossini. 2017. Potential botanical pesticides from Asteraceae essential oils for tomato production: Activity against whiteflies, plants and bees. Ind. Crops Prod. 109: 686–692.

Verheggen, F. and R.B. Fontus. 2019. First record of *Tuta absoluta* in Haïti. Entomologia Generalis 38: 349–353.

Yalçin, M., S. Mermer, L.D. Kozaci and C. Turgut. 2015. Insecticide resistance in two populations of *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) from Turkey. Türk. Entomol. Derg. 39: 137–145.

Zarei, E., S. Ali, A. Fathi, M. Hassanpour and A. Golizadeh. 2019. Assessment of intercropping tomato and sainfoin for the control of *Tuta absoluta* (Meyrick). Crop Prot. 120: 125–133.