Invasion de *Tuta absoluta* au Burkina Faso : Impact, recherche et propositions de stratégies de gestion

Wendnéyidé Mathieu SAWADOGO

Promoteur : Professeur François VERHEGGEN (Université de Liège, Belgique)

Co-promoteur : Professeur Irénée SOMDA (Université Nazi Boni, Burkina Faso)

COMMUNAUTÉ FRANÇAISE DE BELGIQUE
UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

Invasion de *Tuta absoluta* au Burkina Faso : Impact, recherche et propositions de stratégies de gestion.

Wendnéyidé Mathieu SAWADOGO

Dissertation présentée en vue de l'obtention du grade de docteur en sciences agronomiques et ingénierie biologique

Promoteur : Professeur François VERHEGGEN (Université de Liège, Belgique)

Co-promoteur : Professeur Irénée SOMDA (Université Nazi Boni, Burkina Faso)

Année civile : 2021

A Wendziiri Moussoni Doriane SAWADOGO

Wendnéyidé Mathieu SAWADOGO (2021) Invasion de *Tuta absoluta* au Burkina Faso : Impact, recherche et propositions de stratégies de gestion (Thèse de doctorat). Université de Liège, Gembloux Agro-Bio Tech, Belgique (210 pages, 30 Figures, 15 Tableaux).

Résumé :

La mineuse sud-américaine de la tomate *Tuta absoluta* (Meyrick, 1917) (Lepidoptera : Gelechiidae) est l'un des ravageurs les plus redoutés de la tomate. Elle a été découverte en 2016 au Burkina Faso, un pays où la filière tomate joue un rôle socio-économique et nutritionnel très important. Cette thèse a été initiée pour acquérir les connaissances nécessaires au développement de recommandations et méthodes de lutte contre cette espèce exotique envahissante.

Les résultats d'enquêtes menées auprès des producteurs de tomate burkinabés suggèrent que ceux-ci subissent d'énormes pertes économiques qui les obligent à faire un usage déraisonnable, et souvent infructueux, d'insecticides chimiques de synthèse. En évaluant le niveau de résistance développé par les populations de mineuses, nous avons pu établir une liste positive de produits phytosanitaires encore efficaces. Des insecticides biologiques à base d'extraits végétaux atteignent également un niveau d'efficacité larvicide satisfaisant.

La phénologie de cette espèce a été caractérisée durant deux années complètes, suggérant deux pics annuels d'abondance du ravageur. L'espèce réalise une reproduction sexuée toute l'année, mais en cas d'absence de mâle, pratique une reproduction parthénogénétique deutérotoque.

Parmi les alternatives aux pesticides identifiées durant ce travail, nous avons démontré que *Nesidiocoris tenuis* (Hemiptera : Miridae), prédateur des œufs et des jeunes larves de la mineuse, est présent et abondant dans de nombreuses surfaces agricoles du pays et pourrait être un allié de choix si des pesticides biologiques sont préférés aux insecticides de synthèse. De même, nos essais démontrent que *Gynandropsis gynandra* (Capparaceae), une plante potagère comestible et très appétente pour *N. tenuis*, pourrait favoriser le maintien et la prolifération du prédateur dans les champs de tomates. Aussi, nous avons montré que les variétés de tomate Mongal, Cobra 26 F1 et Kanon F1 ont les meilleures aptitudes à contenir les attaques de la mineuse.

Des stratégies de lutte intégrée, valorisant judicieusement ces différents résultats, permettraient de contenir les invasions de cette mineuse au Burkina Faso. Parmi les solutions présentées au terme de ce travail : la modification des périodes de semi et récolte, l'arrachage des plantes hôtes alternatives du genre *Solanum*, l'emploi de biocides efficaces et respectueux des espèces locales, et d'autres approches agroécologiques destinées à favoriser les populations d'ennemis naturels.

Mots clés : *Tuta absoluta*, espèce invasive, phénologie, parthénogenèse, résistance aux pesticides, *Nesidiocoris tenuis*, *Gynandropsis gynandra*, Burkina Faso, *Solanum*, Mongal, Kanon F1, Cobra 26 F1.

Wendnéyidé Mathieu SAWADOGO (2021) *Tuta absoluta* invasion in Burkina Faso: Impact, research and proposed management strategies (PhD thesis). Université de Liège, Gembloux Agro-Bio Tech, Belgium (210 pages, 30 Figures, 15 Tables).

Abstract:

The South American tomato leafminer *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) is one of the most feared pests of tomato. It was discovered in 2016 in Burkina Faso, a country where the tomato sector plays a very important socio-economic and nutritional role. This thesis was initiated to acquire the necessary knowledge to develop recommendations and control methods against this invasive alien species.

The results of surveys conducted among Burkinabe tomato growers suggest that they suffer enormous economic losses that force them to make unreasonable, and often unsuccessful, use of synthetic chemical insecticides. By assessing the level of resistance developed by the leafminer populations, we were able to establish a positive list of still effective plant protection products. Biological insecticides based on plant extracts also achieve a satisfactory level of larvicidal efficacy.

The phenology of this species has been characterised for two full years, suggesting two annual peaks in pest abundance. The species reproduces sexually throughout the year, but in the absence of a male, it practices deuterotokous parthenogenetic reproduction.

Among the alternatives to pesticides identified during this work, we demonstrated that *Nesidiocoris tenuis* (Hemiptera: Miridae), a predator of the eggs and young larvae of the leafminer, is present and abundant in many agricultural areas of the country and could be an ally of choice if biological pesticides are preferred to synthetic insecticides. Similarly, our trials show that *Gynandropsis gynandra* (Capparaceae), an edible vegetable plant that is highly palatable to *N. tenuis*, could favour the maintenance and proliferation of the predator in tomato fields. Also, we have shown that the tomato varieties Mongal, Cobra 26 F1 and Kanon F1 have the best ability to contain leafminer attacks.

Integrated pest management strategies, making judicious use of these different results, would make it possible to contain the invasion of this leafminer in Burkina Faso. Among the solutions presented at the end of this work: modification of the semi and harvest periods, uprooting of alternative host plants of the *Solanum* genus, the use of effective biocides that respect local species, and other agroecological approaches designed to favour natural enemy populations.

Keywords: *Tuta absoluta*, invasive species, phenology, parthenogenesis, pesticide resistance, *Nesidiocoris tenuis*, *Gynandropsis gynandra*, Burkina Faso, *Solanum*, Mongal, Kanon F1, Cobra 26 F1

Remerciements

La fin de cette aventure, qui m'a beaucoup enrichi en termes de connaissances théoriques et pratiques, et qui a façonné ma façon de penser et de résoudre de nouveaux problèmes, n'aurait pas eu de dénouement heureux sans le soutien indéfectible d'un certain nombre de personnes et d'organisations. A travers cette rubrique, je souhaite leur exprimer ma gratitude et mes sincères remerciements. Mes remerciements vont à :

- L'Académie de Recherche et d'Enseignement Supérieur (ARES) de Belgique, qui a entièrement financé cette thèse dans le cadre du projet " Production Durable Intégrant la Recherche (ProDuIRe) ". Nous tenons à remercier ses premiers responsables ;
- Professeur Anne LEGREVE, Coordinatrice Nord dudit projet, qui n'a ménagé aucun effort pour nous accompagner ;
- Professeur François VERHEGGEN, qui a suivi toutes nos activités du début à la fin. Nous tenons à vous remercier pour votre disponibilité, pour votre engagement à nos côtés, pour vos suggestions et corrections malgré vos nombreuses obligations académiques. Vous avez même accepté que je vous vole une bonne partie de votre année sabbatique pour le suivi et la correction de nos différents manuscrits. Merci beaucoup !
- Professeur Irénée SOMDA, Coordinateur Sud du projet ProDuIRe et également mon promoteur au Burkina Faso, qui a su mettre à ma disposition toutes mes sollicitations pour la conduite de ce travail de recherche. Merci pour les nombreuses corrections, suggestions, pour la rigueur dans le travail bien fait que j'essaie de copier et de m'inspirer ;
- Professeur Souleymane NACRO, Chercheur à l'Institut de l'Environnement et de la Recherche Agricole de Kamboinsin (INERA), pour ses suggestions, ses corrections de manuscrits et le suivi de certaines activités sur le terrain ;
- Aux membres de mon comité de thèse pour le suivi et l'approbation de mes activités de recherche et aux membres du jury qui ont accepté évaluer mon travail. Chers enseignants, je vous suis très reconnaissant ;
- Aux autorités du Ministère de l'Agriculture, des Aménagements Hydrauliques et de la Mécanisation du Burkina Faso, pour avoir accepté de me mettre en position de stage, me libérant ainsi de mes obligations professionnelles ;

- Aux autorités administratives et au personnel de l'Université Nazi Boni de Bobo-Dioulasso (Burkina Faso) et de l'Université de Liège Gembloux (Belgique), pour l'accueil et l'environnement de travail qu'ils ont créé et qui m'ont permis de mener à bien mes recherches ;
- A toute l'équipe du projet ProDuIRe au Burkina Faso, avec qui j'ai eu des rencontres de travail très enrichissantes ;
- Aux animateurs des antennes relais de la clinique des plantes (Bobo-Dioulasso, Loumbila, Ouahigouya et Di), qui ont accepté de m'accompagner sur le terrain chaque fois que je les ai sollicités ;
- Aux enseignants-chercheurs du laboratoire SyNAIE (Systèmes Naturels, Agrosystèmes et Ingénierie de l'Environnement), Dr Schémaéza BONZI, Dr Gaston T. DABIRE, Dr Dikalia SON, et Mr Ollo PALE, et aux personnels de la Clinique des Plantes de l'Institut du Développement Rural, Mrs Amadou SANOU, Maxim OUATTARA, pour leur accompagnement ;
- Aux doctorants Mme Assita TIENDREBEOGO, Malik GARANE et Besmer Régis AHISSOU pour leurs soutiens multiformes et les agréables moments passés ensemble ;
- Aux stagiaires ingénieurs et Master, Tièro-Wè Chris Julius DABIRE, Issa BELEM, Yacouba KONATE, Alex MILLOGO, Dominique Ouédraogo, Emmanuel ZERBO, Barakissa CISSE, qui m'ont aidé dans la collecte de mes données et pour la bonne ambiance de travail ;
- Mr et Mme GODART, ainsi que l'Apôtre Daouda KODIO et le Pasteur Féniel PHILIPPE pour leurs soutiens multiformes et les bons moments passés ensemble ;
- A mes parents, mes frères et sœurs, mon épouse (Madjouma SAWADOGO / OUATTARA) et mes enfants (Eben-Ezer, Pétronille et Doriane) qui ont su supporter mes absences pendant la réalisation de cette thèse ;
- Vous tous qui avez contribué d'une manière ou d'une autre, vos noms ne sont hélas pas mentionnés ; loin d'être oubliés, je vous assure de ma profonde gratitude pour tous les efforts que vous avez déployés pour m'assurer le succès

Table des matières

Liste des figures

Liste des tableaux

Partie I : Introduction générale et objectifs

Introduction générale

Le Burkina Faso est un pays enclavé d'Afrique subsaharienne avec une population estimée à 20,5 millions d'habitants en 2020, dont les ¾ vivent en zone rurale (Thiombiano, 2020). Il s'étend sur une superficie de 274 200 kilomètres carrés (MINEFIDE, 2016). L'agriculture est la principale source de revenus des populations les plus pauvres et le pilier de la sécurité alimentaire du pays. Elle emploie plus de 80% de la population active et contribue pour environ 28 à 31% au produit intérieur brut (PIB) (MAH, 2011; MINEFIDE, 2016). Les cultures pluviales (1er mai au 30 septembre) sont principalement basées sur la production de céréales (sorgho, maïs, riz, fonio) et de cultures de rente (coton, sésame, arachide, soja) (MAAH, 2020), tandis que les cultures de contre-saison (1er octobre de l'année N au 30 avril de l'année N+1) sont consacrées au maraîchage (MAH, 2011) qui a été essentiellement introduit par l'administration coloniale dans les années 1930 sur les sites rizicoles de l'Office du Niger (Mali) (Ouedraogo, 1995). Le maraîchage est pratiqué dans toutes les régions du pays (plus de 4 844 sites maraîchers) avec une prédominance dans les régions de la Boucle du Mouhoun, du Nord, des Hauts-Bassins et du Centre-Sud (MAAH, 2020; MAH, 2011). Les principales spéculations produites en 2018 sont les oignons bulbes (362 480 tonnes), les choux (205 177 tonnes), les tomates (167 400 tonnes), l'oignon feuille (45 800 tonnes), les aubergines locales (39 566 tonnes), les aubergines importées (28 295 tonnes), le piment (22 456 tonnes), le haricot vert (8 309 tonnes) et la laitue (7 346 tonnes) (MAAH, 2020). Ainsi, la tomate, deuxième culture légumière en termes de superficie (10 284 hectares) après l'oignon bulbe (19 756 ha) et troisième en termes de production après l'oignon bulbe et le chou, joue un rôle socio-économique et nutritionnel très important pour les populations. Elle a rapporté plus de 78.8 milliards de francs CFA (118,910,220 €) en 2018 aux acteurs du secteur (MAAH, 2019). La production de la tomate pourrait être plus rentable pour le pays si certaines contraintes, dont entre autres les dommages causés par les ravageurs des cultures, étaient levées. En effet, en plus des ravageurs préexistants (aleurodes, acariens, nématodes à galles, lépidoptères foreurs de fruits) qui avaient déjà un impact négatif sur la production (Son, 2018; Son et al., 2018), le pays a été envahi en 2016 par la mineuse sud-américaine de la tomate *Tuta absoluta* (Meyrick) (Son et al., 2017a).

Ce lépidoptère de la famille des Gelechiidae est considéré comme l'un des ravageurs les plus dévastateurs de la tomate dans son aire d'origine (Barrientos et al., 1998; Miranda et al., 1998; Siqueira et al., 2000a). Après son introduction accidentelle en Europe (Espagne) en 2006 (Urbaneja et al., 2007) à partir d'une population chilienne (Guillemaud et al., 2015), il s'est propagé à un rythme de 800 km/an vers l'est et le sud (Biondi et al., 2018). Il a atteint l'Afrique du Nord en 2008 (Ouardi et al., 2012) et s'est propagé le long de la côte méditerranéenne (Desneux et al., 2011, 2010). Il est arrivé en Afrique de l'Ouest en 2010 (USDA-APHIS, 2011). Son cycle de vie passe par 4 stades (œuf, larve, pupe et adulte) dont seul le stade larvaire cause des dommages aux plantes. Elles se nourrissent de toutes les parties aériennes de la plante, détruisant les organes végétatifs et reproducteurs, y compris les fruits mûrs et non mûrs (Desneux et al., 2010). La principale plante hôte de ce ravageur reste la tomate (*Solanum lycopersicum* L.), mais il se nourrit également d'autres solanacées comme la pomme de terre (*Solanum tuberosum* L.), l'aubergine (*Solanum melongena* L.), le pépino (*Solanum muricatum* Aiton) et la morelle (*Solanum nigrum* L.) (Cherif & Verheggen, 2019).

Compte tenu de sa grande capacité de prolifération (10 à 12 générations par an, 260 œufs/femelle) (Fernandez & Montagne., 1990; Germain et al., 2009; Uchoa-Fernandes et al., 1995) et surtout de sa résistance avérée à plusieurs molécules synthétiques, qui est la principale arme utilisée par les producteurs pour lutter contre ce ravageur (Guedes et al., 2019 ; Sawadogo et al., 2020b), il peut entraîner non seulement des pertes de production pouvant atteindre 100 % en l'absence de mesures de contrôle efficaces, mais aussi une augmentation considérable des coûts de production (Badaoui & Berkani, 2011; Desneux et al., 2010; Germain et al., 2009).

Il convient donc d'accorder une attention particulière à ce ravageur invasif, non seulement pour s'assurer qu'il ne cause pas de dommages importants, mais aussi pour rechercher des stratégies de gestion respectueuses de l'environnement qui puissent garantir les moyens de subsistance des producteurs de légumes.

Ainsi, des études sur sa biologie, son écologie, les facteurs favorables et défavorables à son développement et à son expansion, ainsi que des stratégies de gestion intégrée efficaces et durables contre ce ravageur doivent être menées.

C'est dans ce contexte que la présente thèse de doctorat intitulée "**Invasion de *Tuta absoluta* (Meyrick) au Burkina Faso : Impact, recherche et propositions de stratégies de gestion**" a été initiée.

Objectifs de la thèse

L'objectif général de cette thèse est d'améliorer la productivité du secteur de la tomate en réduisant considérablement la prévalence et les dégâts causés par *T. absoluta* grâce à des propositions de stratégies de lutte respectueuses de l'environnement et de la santé des agriculteurs.

Plus spécifiquement, cette thèse s'est fixée les objectifs spécifiques suivants :

- Dresser l'état des connaissances sur l'invasion de *T. absoluta* au Burkina Faso et évaluer son impact agricole et socio-économique ;
- Caractériser la phénologie du ravageur pour proposer un calendrier agricole
- Vérifier la capacité des populations de *T. absoluta* présentes au Burkina Faso à se reproduire par parthénogenèse et en tirer les conséquences en termes de lutte ;
- Évaluer l'efficacité des biopesticides ainsi que des produits chimiques de synthèse disponibles pour obtenir une liste positive de molécules efficaces contre la mineuse ;
- Rechercher des agents de contrôle efficaces et des stratégies pour leur maintien et leur prolifération dans les parcelles de production et qui peuvent être facilement vulgarisés auprès des producteurs ;
- Cribler les principales variétés de tomates produites au Burkina Faso pour déterminer celles qui sont les plus tolérantes à *T. absoluta*.
- Déterminer les cultures hôtes de la mineuse afin d'envisager une lutte par la création d'un vide sanitaire à grande échelle ;

Cette thèse est donc constituée de six parties :

- La première partie concerne l'introduction générale et les objectifs poursuivis ;
- La deuxième partie est une synthèse bibliographique des différentes stratégies de lutte contre *T. absoluta* pouvant être mises en œuvre au Burkina Faso. Elle présente également l'impact de *T. absoluta* dans le pays. Ceci nous permettra de répondre à notre objectif spécifique 1 ;
- La troisième partie traite de la phénologie et des modes de reproduction de la mineuse. Cela nous permettra de justifier nos objectifs spécifiques 2 et 3 ;
- La quatrième partie concerne la recherche d'une liste positive de produits biologiques et de molécules synthétiques contre *T. absoluta*. Ceci permettra de répondre à notre objectif spécifique 4;
- La cinquième partie concerne la recherche de méthodes alternatives aux pesticides. Cette partie nous permettra d'atteindre nos objectifs spécifiques 5, 6 et 7 ;
- La sixième partie traite de la discussion des résultats, et présente les conclusions, recommandations et perspectives sur la gestion de la mineuse au Burkina Faso.

Partie II : Synthèse bibliographique et situation de référence

Chapitre II.1

La production de tomate au Burkina Faso face à l'invasion de la mineuse *Tuta absoluta*

Chapitre II. 1 : La production de tomate au Burkina Faso face à l'invasion de la mineuse *Tuta absoluta*

1. La tomate

1.1 Origine et bio écologie

La tomate (*Solanum lycopersicum* L.) (Solanales : Solanaceae) est originaire des Andes d'Amérique du Sud (Naika et al., 2005). Elle a été domestiquée au Mexique à partir de la tomate cerise (*S. lycopersicum* var. cerasiforme) (Blanca et al., 2012) et a été introduite en Europe en 1544. De là, sa culture s'est répandue en Asie du Sud et de l'Est, en Afrique et au Moyen-Orient (Naika et al., 2005). En 1694, Tournefort distingue la tomate cultivée et la classe dans le genre Lycopersicum (Peralta & Spooner, 2007). En 1753, Linnaeus l'a inclus dans le genre *Solanum* et un an plus tard, Miller l'a replacé dans le genre Lycopersicon (Ranc, 2010). Sur la base des techniques modernes de biologie moléculaire, la taxonomie actuelle a replacé la tomate dans le genre *Solanum* (Spooner et al., 1993).

C'est une plante herbacée cultivée comme une annuelle ou pluriannuelle en Amérique du Sud. Cependant, il existe deux types de croissance : la croissance déterminée et la croissance indéterminée (Naika et al., 2005). La première inflorescence (4-12 fleurs) se produit lorsque la plante a 7-14 feuilles composées ou 56-70 jours selon les variétés. La maturation des fruits se situe entre 42 et 56 jours après le développement complet des fleurs. Avec un cycle de production de 80-120 jours (Spooner et al., 1993), elle a un port érigé en début de croissance, puis retombant ou semi-tombant au fur et à mesure que la tige se développe et se ramifie, ce qui nécessite des supports variables selon le type de culture.

Elle préfère les sols minéraux avec une bonne capacité de rétention d'eau, une bonne aération, sans sels et avec un pH entre 5,5 et 6,8. Elle pousse également bien sur des sols limoneux profonds et bien drainés (Naika et al., 2005). La culture nécessite une fumure de fond de 30 à 50 t.ha^{-1} de matière organique et 300 kg.ha^{-1} de NPK (12-22-22 ou 14-23-14) (Rouamba et al., 2013). Les températures optimales sont fixées entre 21 et 24 °C et en dessous de 10 °C et au-dessus de 38 °C, les tissus des plantes sont endommagés (Naika et al., 2005).

1.2 Production de la tomate dans le monde

La tomate est produite dans toutes les zones climatiques du monde (5 030 545 ha, 180 766 329 tonnes, 178 pays en 2019), y compris dans les régions relativement froides grâce au développement des cultures sous abri. 62,1% de la production mondiale est assurée par les cinq plus grands producteurs, à savoir la Chine (34,8%), l'Inde (10,5%), la Turquie (7,1%), les Etats-Unis (6,0%) et l'Egypte (3,8%). La production africaine (1 612 512 ha, 21 664 774 tonnes) ne représente que 12% de la production mondiale. L'Egypte (31,2%), le Nigeria (17,6%), l'Algérie (6,8%) et le Maroc (6,2%) sont les plus gros producteurs (FAOSTAT, 2021).

1.3 La filière tomate au Burkina Faso

1.3.1 Production de la tomate

Pour la campagne maraîchère 2018-2019, la tomate s'était placée au deuxième rang en termes de superficie (10 284 ha) après l'oignon (19 756 ha) et au troisième rang en termes de masse (167 400 tonnes) de produit derrière l'oignon (362 480 tonnes) et le chou (205 177 tonnes). Le rendement national a été de 21 tonnes par ha (MAAH, 2020, 2019).

1.3.2 Importance de la filière tomate

En plus de sa contribution à l'équilibre alimentaire des populations (riche en vitamines B et C, de fer et de phosphore et en fibres) (Naika et al., 2005), la production de tomate joue un rôle socio-économique très important. Sa production occupe une grande partie des agriculteurs pendant la saison sèche (30% des producteurs) et génère des revenus importants pour les acteurs de la filière (producteurs, distributeurs, transformateurs…). Avec une valeur de vente estimée à 17,5 milliards CFA (26,678,575 €) en 2008, soit 21% du chiffre d'affaires du maraîchage (MAH, 2011), elle a rapporté 4,5 fois plus de revenus aux acteurs en 2018 (78,8 milliards CFA (120,129,812 €) en 2018, soit environ 28% du chiffre d'affaires du maraîchage) (MAAH, 2019).

1.3.3 Contraintes liées à la production de la tomate au Burkina Faso

Plusieurs contraintes abiotiques et biotiques entravent le bon fonctionnement de la filière tomate. Les contraintes abiotiques sont d'ordre technique, financier et organisationnel. Selon MAH, 2011, ces contraintes sont :

- la non disponibilité et/ou le coût élevé des intrants de qualité (semences, produits phytosanitaires adéquats et engrais adaptés) ;
- les difficultés d'accès aux équipements d'irrigation (motopompes, tuyaux PVC), ainsi que l'insuffisance et le tarissement précoce des points d'eau ;
- la faible maîtrise des techniques culturales, notamment celles concernant la préparation du sol, la fertilisation et la lutte contre les principaux ravageurs et maladies ;

- les difficultés liées à l'accès au crédit agricole, qui se traduisent par l'absence d'institutions de microfinance (IMF), la complexité des procédures de demande de crédit, le taux d'intérêt élevé et la brièveté de la période de remboursement ;
- les difficultés de commercialisation dues au manque d'unités de transformation, au faible prix des produits maraîchers, à l'éloignement des centres de vente, au mauvais état des routes et à la mauvaise qualité des produits due principalement à la pression des ravageurs.

Quant aux contraintes biotiques, elles concernent les ennemis des cultures, notamment les maladies, les ravageurs et les mauvaises herbes (Naika et al., 2005). La prévention des maladies et des ravageurs est extrêmement importante pour la culture de la tomate. Selon Son, 2018, les principales maladies rencontrées sont l'alternariose (*Alternaria dauci* f. sp. *solani*), la fusariose (*Fusarium oxysporum* f. sp. *Lycopersici*), la pourriture molle (*Erwinia* spp), le *Tomato Yellow Leaf Cure Virus* (TYLCV) et le *Tomato Mosaic Virus* (TMV). Les ravageurs comprennent les aleurodes (*Bemisia tabaci*, Gennaduis), la noctuelle de la tomate (*Helicoverpa armigera*, Hubner), les acariens (*Aculops lycopersici*, Tryon) et les nématodes (*Meloidogyne incognita*, Kofoid et White et *Meloidogyne javanica*, Treub). En plus de ces ravageurs préexistants, le pays a été envahi par la mineuse sud-américaine de la tomate *Tuta absoluta* Meyrick (Lepidoptera : Gelechiidae) l’un des ravageurs les plus redoutés de la tomate dans le monde. Pour y faire face, plusieurs stratégies de lutte telles que la rotation des cultures, le désherbage, l'utilisation de variétés résistantes (hybrides), l'utilisation de l'irrigation par aspersion ont été développées (Biondi et al., 2018). Cependant l'utilisation de pesticides, souvent déraisonnée, reste la méthode de lutte la plus courante (Son, 2018; Son et al., 2017a, 2017b).

2. *Tuta absoluta* Meyrick

2.1 Taxonomie

Décrit pour la première fois en 1917 à partir de spécimens provenant de Huancayo (Pérou), Meyrick lui avait donné le nom de *Phthorimaea absoluta*. Par la suite, il a été classé dans les genres *Gnorimoschema* en 1962, *Scrobipalpula* en 1964 et *Scrobipalpuloides* en 1987. C’est en 1994 où il a été appelé *Tuta absoluta* ou mineuse sud-américaine de la tomate par Povolný (Biondi et al., 2018; Povolný, 1994).

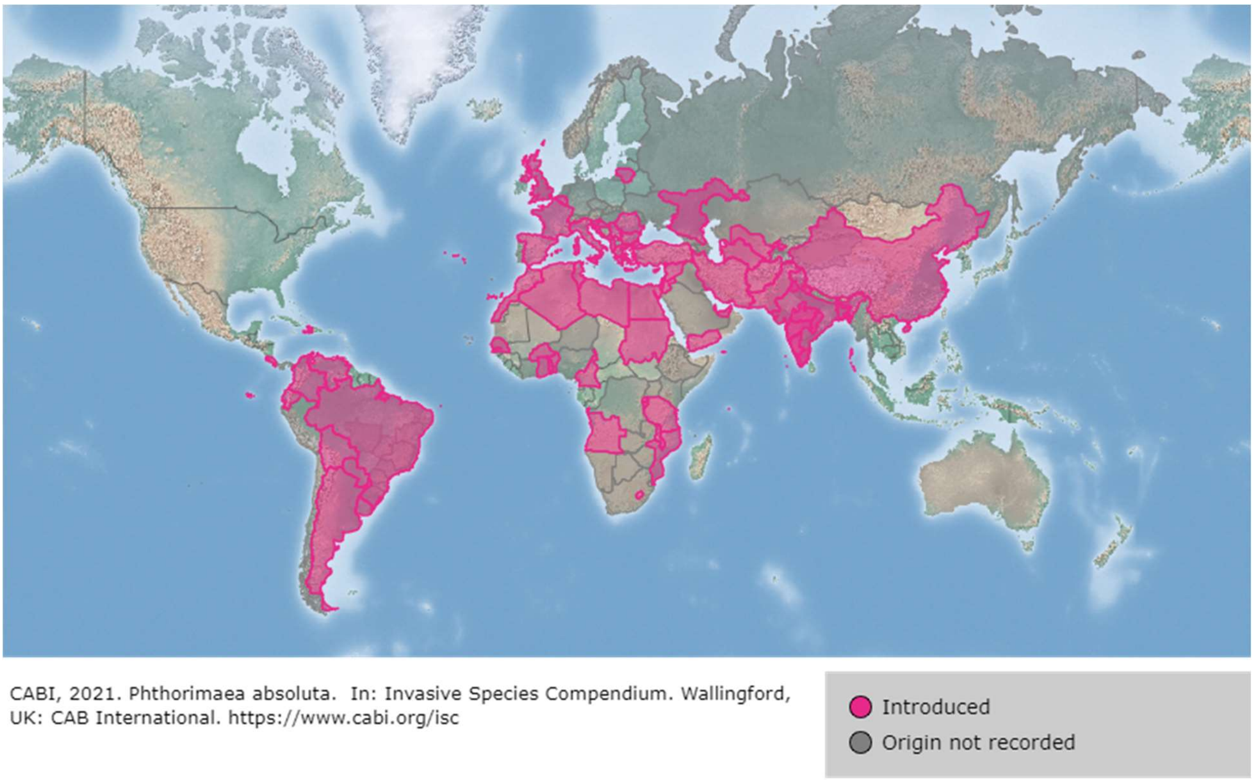
C'est une mineuse de la famille des Gelechiidae, un taxon qui comprend plus de 4000 espèces, dont certaines sont des ravageurs de la pomme de terre (*Tecia solanivora* et *Phthorimaea* *operculella* ou de la tomate (*Keiferia lycopersicella*). Ces deux derniers ravageurs sont morphologiquement identiques à *T. absoluta* et l'utilisation de codes-barres sur les gènes de la cytochrome oxydase I (COI) ou l'examen de la forme de la valve et du vinculum dans les organes génitaux mâles peuvent aider à les différencier (Badaoui & Berkani, 2011; Biondi et al., 2018a; Crespo-Pérez et al., 2014; Son et al., 2017a; Zhang et al., 2013).

Selon Povolný, 1994, la position systématique de *T. absoluta* se présente comme suit

Règne: *Animalia*
  Phylum: *Arthropoda*
    Classe : *Insecta*
      Ordre : *Lepidoptera*
        Sous-ordre *: Glossata*
          Super-famille : *Gelechioidea*
            Famille *: Gelechiidae*
              Sous famille : *Gelechiinae*
                Genre : *Tuta*
                  Espèce : *Tuta absoluta* Meyrick (1917)

2.2 Origine et distribution

Tuta absoluta serait originaire des hauts plateaux du centre de Pérou et non pas d'Amérique centrale comme initialement décrit. De là, il se serait répandu dans les pays d'Amérique latine au cours des années 1960 (Biondi et al., 2018; Desneux et al., 2011). Il a été détecté au Chili en 1935, en Argentine en 1964, en Bolivie et au Brésil en 1980 (Badaoui, 2018; Siqueira et al., 2001). Après plus de 50 ans de présence en Amérique latine, et à partir d'une population chilienne de la mineuse (Guillemaud et al., 2015), elle a été signalée pour la première fois en Espagne en 2006 (Urbaneja et al., 2007). Depuis lors, elle s'est propagée à un rythme moyen de 800 km par an vers l'est et le sud et est devenue un ravageur presque mondial puisqu'elle a atteint l'Afrique, l'Asie, les Caraïbes et tout récemment la Chine, à l'exception des États-Unis (figure 1) qui est l'un des grands producteurs de tomates (Biondi et al., 2018a; Mansour et al., 2018; Santana et al., 2019; Verheggen & Fontus, 2019; Zhang et al., 2020). En 8 ans, de sa première détection au Maroc en 2008, à son arrivée en Afrique du Sud en 2016, la quasi-totalité de l'Afrique a été envahie (Badaoui, 2018; Son et al., 2017a; Sylla et al., 2017), à l'exception des pays du sud-ouest du continent. Cependant, USDA-APHIS estime qu'elle est présente dans la plupart de ces pays (Biondi et al., 2018; USDA-APHIS, 2011, 2014).



CABI, 2021. Phthorimaea absoluta. In: Invasive Species Compendium. Wallingford, UK: CAB International. https://www.cabi.org/isc

Figure 1 : Répartition géographique de *T. absoluta*

2.3 Bio-écologie de *Tuta absoluta*

T. absoluta est un lépidoptère diploïde (2n = 58 chromosomes). Sa paire de chromosomes sexuels mâles est ZZ et celle des femelles WZ (Paladino et al., 2016). Les adultes sont des papillons mesurant 7 mm, avec une envergure de 10-11 mm et des ailes antérieures de 4,5-4,7 mm. Ils sont de couleur gris cendré avec quelques taches noires. Les antennes annelées font 5/6 la longueur de leur corps. A ce stade, l'identification certaine de l'espèce passe par l'observation des organes génitaux des mâles (Germain et al., 2009). Les femelles sont plus grandes que les mâles et vivent de 10 à 15 jours, tandis que les mâles vivent de 6 à 7 jours (Estay, 2000; Koudjil et al., 2015). Les mâles sont polygames et les femelles polyandres. La communication pour la reproduction repose sur les phéromones sexuelles des femelles, et l'accouplement dure de quelques minutes à six heures (Lee et al., 2014). Ils s'accouplent en moyenne 6,5 fois mais peuvent le faire 12 fois de suite. Elles peuvent pondre jusqu'à 260 œufs (Silva, 2008). Elle est capable de se reproduire par parthénogenèse deutérotoque (Abbes & Chermiti, 2014; Caparros Megido et al., 2012).

Les œufs sont de petite taille, 0,36 mm de long et 0,22 mm de large, de forme cylindrique et de couleur crème à jaunâtre. Ils sont pondus individuellement ou en groupes de 5 œufs au maximum, de préférence sur la face inférieure des jeunes feuilles dans les parties supérieures de la plante, ou sur les tiges, les sépales et, dans une moindre mesure, les fruits (Biondi et al., 2018; Cocco et al., 2015). L'incubation des œufs dure 4 à 5 jours mais est fonction de la température ambiante (Cuthbertson et al., 2013).

La larve passe par quatre stades dont un stade baladeur (L1). Elles sont initialement de couleur crème (1er stade), puis deviennent verdâtres et rose clair (2ème-4ème stade). La largeur de la capsule céphalique varie entre 0,12 et 0,6 mm, tandis que sa longueur varie de 0,42 à 7,25 mm, la taille de la larve L4 pouvant être jusqu'à 10 fois supérieure à celle de la larve L1 (Grissa-Lebdi et al., 2011). Elles se nourrissent en minant le mésophylle de la feuille, ce qui donne lieu à de grandes galeries blanchâtres et transparentes (il ne subsiste que l'épiderme, le parenchyme étant consommé), contenant chacune une ou plusieurs chenilles et leurs déjections (figure 2) (Estay, 2000). Avec le temps, les galeries se nécrosent et deviennent brunes (Torres-vila et al., 2002). Cela peut réduire considérablement la capacité photosynthétique de la plante. La tige est attaquée à l'insertion de la feuille ou du pédoncule, ce qui nuit généralement au développement de la plante. Les fruits sont attaqués dès leur nouaison sur la face pédonculaire. La larve perfore sa galerie, ce qui déforme le fruit et le rend sensible aux attaques d'agents pathogènes secondaires. En conséquence, la qualité commerciale des fruits est dépréciée (Grissa-Lebdi et al., 2011). Elles peuvent provoquer des dégâts allant jusqu'à 100 % de la production (figure 3) si aucune mesure de contrôle n'est prise (Desneux et al., 2010; Han et al., 2019b). Le stade larvaire dure 13-15 jours mais est fortement influencé par la température (Desneux et al., 2010; Tropea Garzia et al., 2012). Les larves matures tombent généralement au sol à l'aide d'un fil de soie où elles produisent un cocon fin et soyeux et se transforment en pré-pupes puis en chrysalides. Cependant, certaines larves matures se transforment en chrysalides et terminent leur cycle de développement à l'intérieur des galeries (Desneux et al., 2010; Grissa-Lebdi et al., 2011).

Figure 2 : Dégâts de *T. absoluta* sur feuilles (A, B, C), tige (D) et fruits (E, F).

Figure 3 : Sites de production de tomates complètement dévastés par *T. absoluta* au Burkina Faso

La chrysalide mesure 4 à 5 mm de long et est de forme cylindrique. Elle est verte au début et devient brune vers l'éclosion. La durée de ce stade dépend de la température (13,7 jours à 25°C) (Germain et al., 2009; Grissa-Lebdi et al., 2011).

Le cycle de développement de *T. absoluta* peut varier entre 26 et 75 jours en fonction de la température. Les seuils de développement sont compris entre 14°C et 34,6°C avec un optimum à 30°C. *T. absoluta* n'entre pas en diapause mais peut survivre à 0°C (Biondi et al., 2018; Cuthbertson et al., 2013). Le cycle de développement, que nous avons mesuré à 28±3°c et à une humidité relative de 50±15% avec une photopériode de 12 h de lumière et 12 h d’obscurité, est le suivant (figure 4).

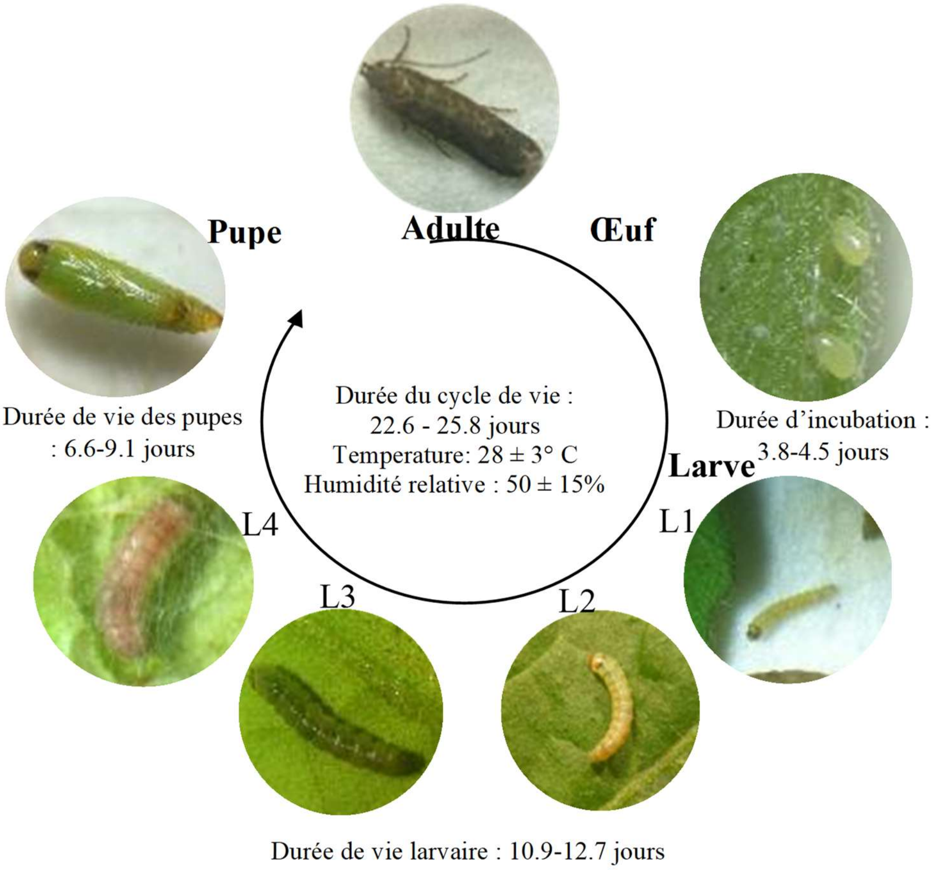


Figure 4 : Cycle de développement de *T. absoluta*

2.4 Plantes hôtes

T. absoluta est signalée comme étant un ravageur des cultures de solanacées d'importance économique (pomme de terre, aubergine, tabac, piment...) et non cultivées (*Solanum. eleagnifolium* L., *S. bonariense* L., *S. sisymbriifolium* Lam., *Lycopersicum puberulum* Ph., *Datura stramonium* L, *Lycium chilense* Mill et *Nicottiana glauca* Graham), mais elle préfère la tomate, sur laquelle elle peut infliger de très lourdes pertes. Cependant, elle peut pondre et accomplir tout ou une partie de son cycle de vie sur plusieurs autres plantes appartenant aux Amaranthaceae, Convolvulaceae, Chenopods, Fabaceae et Malvaceae (Bawin et al., 2016; Cherif & Verheggen, 2019; Desneux et al., 2011, 2010; Koudjil et al., 2015; Portakaldali et al., 2013). Ceci indique que *T. absoluta* montre une forte propension à utiliser diverses plantes comme hôtes secondaires, en particulier celles des Solanaceae.

2.5 Impact de *T. absoluta* dans le monde

T. absoluta est l'un des ravageurs les plus économiquement importants de la tomate dans le monde. L'invasion de ce dernier dans un pays entraîne une augmentation drastique de l'utilisation de pesticides, qui peut aller jusqu'à 30 applications quand l'infestation est importante (Desneux et al., 2011; Guedes & Picanço, 2012). Ainsi, les revenus des producteurs sont affectés directement par la réduction du rendement commercialisable et indirectement par l'augmentation des coûts de production et des investissements dans la lutte contre le ravageur. Les consommateurs seront également affectés non seulement par une augmentation probable du prix d'achat de la tomate mais aussi par les conséquences liées à la présence de résidus de pesticides dans la tomate (Rwomushana et al., 2019). De ce fait, elle est considérée comme un organisme de quarantaine, surtout dans les pays non touchés (États-Unis) (Rwomushana et al., 2019; USDA-APHIS, 2014, 2011). Elle constitue donc une menace pour les pays dont les exportations de tomates sont importantes pour leur économie et une menace majeure pour la durabilité de la production mondiale de tomates (Desneux et al., 2011). En Afrique sub-saharienne, on estime qu'elle cause des pertes annuelles d'environ 791,5 millions de dollars U.S. (Rwomushana et al., 2019).

2.6 Méthodes de lutte

La méthode de lutte la plus utilisée dans sa zone d'origine ainsi que dans ses zones d'invasion reste sans conteste les insecticides chimiques de synthèse à tel point que plusieurs études confirment le développement de résistances à plusieurs molécules (Guedes et al., 2019; Han et al., 2019b; Roditakis et al., 2021, 2018). En outre, compte tenu des effets néfastes que peuvent avoir les pesticides sur la santé humaine, animale et sur l'environnement, il convient d'élaborer des stratégies de lutte efficaces qui maintiennent le ravageur en dessous d'un seuil ingérable et que les pesticides ne soient utilisés que dans les situations où le ravageur a réussi à supplanter ces techniques. Ainsi nous avons parcouru la littérature pour répertorier ces différentes techniques alternatives aux pesticides, efficaces.

2.6.1 Lutte biologique

- **Macro-organismes**

L'utilisation de macro-organismes est l'une des options les plus prometteuses pour le contrôle de *T. absoluta*. Plus de 160 espèces d'auxiliaires lui sont associées dans le monde (Biondi et al., 2018; Ferracini et al., 2019; Lenteren et al., 2019). Dans la région du Paléarctique occidental, plus de 70 espèces d'ennemis naturels généralistes (20% de prédateurs et 80% de parasitoïdes) ont été signalées. Parmi elles, seules quelques espèces de parasitoïdes des familles d'Eulophidae et de Braconidae et de prédateurs Miridae montrent une certaine efficacité qui pourrait être utilisée dans une stratégie de lutte intégrée contre la mineuse (Zappalà et al., 2013). Parmi les Miridae, *Nesidiocoris tenuis* Reuter et *Macrolophus pygmaeus* (Rambur) ont montré une certaine efficacité en laboratoire, en serre et au champ. Ils se nourrissent principalement des œufs et des jeunes larves de *T. absoluta*. Introduits tôt dans la culture de tomate, avant l'arrivée du ravageur, ils peuvent réduire considérablement les pertes dues aux dégâts de *T. absoluta*, améliorant ainsi les rendements (Abbes et al., 2012a; Chailleux et al., 2013b; Mirhosseini et al., 2020). Urbaneja et al., 2012 rapportent qu'une introduction en pépinière de *N. tenuis* a permis de produire 300 ha de tomates à Almeria, en Espagne. Cette expérience a été rééditée l'année qui a suivi et a permis de protéger efficacement 3500 ha de tomates. En serre, une dose de 2 adultes par mètre carré pourrait être nécessaire (Mirhosseini et al., 2020), tandis qu'au champ, 8000 individus par ha ou 0,8 individus par mètre carré seraient nécessaires pour un meilleur contrôle de la mineuse (Abbes et al., 2012a).

Parmi les parasitoïdes, *Trichogramma achaeae* (Nagaraja and Nagarkatti) (Hymenoptera: Trichogrammatidae) pourrait parasiter plus de 90% des œufs de *T. absoluta* dans les serres s'il est lâché à un taux de 75 adultes.m^{-2} tous les 3-4 jours (Cabello et al., 2009). Des lâchers inondatifs (100 points de lâcher.ha^{-1}) de 250 000 à 1 000 000 d'adultes par ha et par semaine sont nécessaires en fonction du niveau d'infestation (Urbaneja et al., 2012). De même, *Trichogramma cacaeciae* (Marchal) (142860 à 238100 adultes par semaine.ha^{-1}) ou *Trichogramma evanescens* (Westwood) (2860 adultes.ha^{-1}), chacun en combinaison avec le piégeage de masse a induit un bon contrôle de la mineuse en Egypte (Goda et al., 2015; Meabeb et al., 2015). *Trichogramma brassicae* (Bezdenko), pourrait interférer négativement et réduire l'efficacité de *N. tenuis* s'ils sont utilisés en association pour la lutte (Ali et al., 2019).

Le parasitoïde *Necremnus tutae* (Ribes & Bernardo) (Hymenoptera : Eulophidae) pourrait avoir un bon contrôle de *T. absoluta* mais a des nombres très élevés (plus de 2 *N. tutae*/ m^2/ semaine) (Calvo et al., 2016). Quant aux parasitoïdes larvaires, *Bracon nigricans* et *Necremnus artynes,* ils demeurent des candidats potentiels pour la lutte contre *T. absoluta* (Ferracini et al., 2019).

- **Micro-organismes**

Plusieurs entomopathogènes ont été formulés pour lutter contre la mineuse des feuilles avec une certaine efficacité. L'efficacité de *Bacillus thuringiensis* var. kurstaki (Btk) contre la mineuse de la tomate a été démontrée depuis 2001 au Brésil (Giustolin et al., 2001). Il est au cœur de la lutte microbienne contre *T. absoluta* à la fois dans sa zone d'origine et dans ces zones envahies où il a montré une certaine efficacité en laboratoire dans des serres et en plein champ contre principalement les larves de premier stade de la mineuse de la tomate. Il pourrait être utilisé en combinaison avec des prédateurs Miridae (Dammak et al., 2015; González-Cabrera et al., 2011; Jamoussi et al., 2013; Sellami et al., 2014).

Le spinosad et le spinétorame, dérivés de la bactérie *Saccharopolyspora spinosa* Mertz & Yao, ont également montré une grande efficacité contre la mineuse et sont utilisés dans plusieurs programmes de contrôle (Nannini et al., 2011; Thompson et al., 2000).

Les champignons les plus couramment utilisés sont *Beauveria bassiana* (Bals. -Criv) Vuill., *Metarhizium anisopliae* (Metchnikoff) Sorokin et *Aspergillus oryzae* (Ahlburg) E. Cohn. Des doses de 10^6 ou 10^8 spores.ml^{-1} en application foliaire de *M. anisopliae* seraient efficaces contre les œufs des deux premiers stades larvaires (Pires et al., 2010, 2009; Rodríguez S. et al., 2006) et pour les pupes la dose devrait être de 5,58 10^9 conidies viables par litre (Contreras et al., 2014). Des mortalités larvaires de 90 à 100 % en laboratoire et de 46 à 75 % en serre ont été obtenues avec une formulation commerciale de *B. bassiana* (Abd El-Ghany et al., 2018; Klieber & Reineke, 2016). Zekeya et al., 2019 ont rapporté qu'une souche tanzanienne de *A. oryzae* (10^8 conidies.ml^{-1}) a induit une mortalité larvaire de 70% en 3 jours.

Deux genres de nématodes *Heterorhabditis (H. amazonensis* JPM4) et *Steinernema* (*S. yirgalemense, S. feltiae et S. feeliae*) se sont révélés efficaces contre *T. absoluta* dans des conditions de laboratoire (Amizadeh et al., 2019; Guevara et al., 2020; Van Damme et al., 2015). Des doses de laboratoire et de serre de 20-50 IJs.cm^{-2} et 150-1000 IJs.ml^{-1} de ces espèces pourraient induire des mortalités larvaires de 89-100% et 12,9-50%, respectivement (Batalla-carrera et al., 2010; Kamali et al., 2017; Ndereyimana et al., 2019a; Sabry et al., 2016).

2.6.2. Lutte sémio-chimique

Elle a l'avantage d'être spécifique, agissant à faibles doses et respectueuse de l'environnement grâce à l'utilisation de phéromones sexuelles naturelles ou synthétiques (Witzgall et al., 2010). La phéromone sexuelle de *T. absoluta* est l'acétate de 3E,8Z,11Z (3,8,11-tétradécatrien-1-yl ou TDTA), composé majeur à 90% et l'acétate de 3E,8Z (3,8-tétradécadién-1-yl ou TDDA), composé mineur à 10% (Cocco et al., 2013; Jallow et al., 2020; Michereff-Filho et al., 2000). Elle permet la détection précoce et le suivi de la dynamique des populations de *T. absoluta* sur le terrain. Elle est également utilisée dans les stratégies de contrôle à travers les techniques de confusion sexuelle et de piégeage de masse.

L'efficacité de la technique de confusion sexuelle dépend du niveau de confinement de la serre, de la dose de phéromone, du nombre de diffuseurs et du niveau d'infestation (Cocco et al., 2013; Jallow et al., 2020; Vacas et al., 2011). Une serre de haut confinement équipée d'un diffuseur constant de 30 $g.ha^{-1}$ pendant 4 mois permet de contrôler *T. absoluta* (Vacas et al., 2011). Une efficacité avec une diffusion de 60 $g.ha^{-1}$ (1000 diffuseurs. ha^{-1} placés à 1,5 m du sol et espacés de 4 m) a également été rapportée par (Cocco et al., 2013; Jallow et al., 2020). Ils ont obtenu une réduction des captures de mâles de 90%, du niveau d'infestation de 57 à 85%, et des dégâts de 62 à 89%. Cependant, en plein champ, Michereff-Filho et al., 2000 ont obtenu des résultats mitigés avec 2500 diffuseurs de 35 à 50 $g.ha^{-1}$ de phéromones sexuelles.

La technique de piégeage de masse combine le piège (à eau avec de l'huile de vidange ou de l'huile végétale, delta, cuvette, ferolite et rouleau) appâté avec de la phéromone (0,5 mg/piège) placé stratégiquement dans le champ (Aksoy & Kovanci, 2016; Lobos et al., 2013; Osman & Agriculture, 2015; Polat, 2019). Son efficacité dépend donc du type de piège, de la phéromone et de leur densité. Des densités de 20-25 pièges par ha en serre et de 40-50 pièges par ha au champ sont recommandées (Aksoy & Kovanci, 2016; Chermiti & Abbes, 2012; Chidege et al., 2018; Lobos et al., 2013) mais pourraient être réduites à 10-12 si l'on y associe l'utilisation de parasitoïdes ou de biopesticides (Abbes et al., 2012 ; Goda et al., 2012). L'ajout d'une lumière LED de 470 nm peut également permettre de capturer les femelles de *T. absoluta* et donnerait même des résultats comparables à ceux des pesticides (Aksoy & Kovanci, 2016; Castresana & Puhl, 2017).

2.6.3 Lutte physique

Elle consiste à l'élimination/destruction des organes attaqués, des débris végétaux ou au brûlage des champs fortement attaqués en fin de saison, au désherbage surtout des mauvaises herbes hôtes, au laboure profond, l'utilisation d'un vide sanitaire d'au moins 6 semaines dans les cultures sous serre (Ouardi et al., 2012).

2.6.4 Lutte culturale

Elle consiste à agir sur les facteurs agronomiques pour défavoriser le ravageur. En cultures irriguées, la réduction des apports d'eau d'irrigation diminue le taux de survie, la masse nymphale et ralentit le développement larvaire (Han et al., 2016, 2014). De même, l'utilisation judicieuse de l'azote induisant un rapport C/N foliaire plus élevé, et une accumulation des composés phénoliques constitutifs et des glyco-alcaloïdes dans les feuilles, réduit la survie des larves et allonge le développement de l'insecte (Blazhevski et al., 2018; Han et al., 2016; Larbat et al., 2016). Elle consiste également en une association de cultures entre la tomate et la coriandre ou avec du sainfoin ou du sésame (Biondi et al., 2016; Zarei et al., 2019).

2.6.5 Lutte génétique

C'est l'une des meilleures techniques de lutte car elle ne nécessite pas un niveau de technicité élevé des producteurs. Le développement de variétés résistantes à *T. absoluta* est toujours au stade de recherche/développement. Il est basé sur les espèces de tomates sauvages qui, grâce aux trichomes glandulaires (Leite et al., 2000), produisent des substances défensives telles que des alcaloïdes, des composés phénoliques et des terpènes, chose que la plupart des variétés cultivées ont perdu (Bleeker et al., 2012). La grande difficulté de l'amélioration variétale est que les variétés résistantes perdent leur capacité à donner de bons rendements (Guedes & Picanço, 2012). Néanmoins, certaines variétés commerciales ont montré une tolérance à *T. absoluta* (Gharekhani & Salek-Ebrahimi, 2014a; Sohrabi et al., 2016).

2.6.6 Insecticides botaniques

Ce sont des pesticides d'origine végétale utilisés sous forme d'huiles essentielles, d'huiles végétales, d'extraits aqueux, d'extraits méthanoliques, en pulvérisation ou par fumigation.

Les huiles essentielles de Zingiberaceae (*Elettaria cardamomum*) (Chegini & Abbasipour, 2017), Lamiaceae (*Zataria multiflora*) (Chegini et al., 2018) et *Thymus capitatus* et Cupressaceae (*Tetraclinis articulata*) (Alam et al., 2017) et les écorces d'agrumes (Campolo et al., 2017) ont donné des résultats satisfaisants sur la mineuse de la tomate.

Des extraits méthanoliques et des huiles végétales de *Thymus vulgaris* (Lamiaceae), *Ricinus communis* (Euphhorbiaceae), *Peganum harmala* (Nitrariaceae) et *Urtica dioica* (Urticaceae) ont entraîné des mortalités larvaires de *T. absoluta* supérieures à 60 % (Ait Taadaouit et al., 2012; Campolo et al., 2017).

Les formulations émulsifiables d'*Azadirachtine indica* (Meliaceae) et d'orange (citrus) ont entraîné une mortalité larvaire de 70 à 80 % (Abd El-Ghany et al., 2018; Campolo et al., 2017).

Chapitre II.2

Cinq années d’invasion : Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso

Chapitre II.2 : Cinq années d’invasion : Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso

Ce chapitre est une version adaptée de l'article

SAWADOGO, M.W., SOMDA, I., NACRO, S., LEGRÈVE, A. & VERHEGGEN, F. 2020. Cinq années d’invasion : Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso. *Tropicultura* ***38***, 1–14. DOI: 10.25518/2295-8010.1638

Résumé

Tuta absoluta est un micro-lépidoptère originaire d’Amérique du Sud et recensé au Burkina Faso depuis 2016. Ses larves creusent des galeries dans les feuilles et les fruits de la tomate. Grâce à des enquêtes détaillées réalisées auprès de 180 producteurs, nous avons évalué l’impact de ce ravageur sur la culture de tomates. Les cultivateurs produisent la tomate sur des superficies inférieures à ½ hectare. Tous ont démontré leur connaissance de *T. absoluta* et peuvent en décrire les symptômes. En moyenne, les producteurs estiment que cette mineuse leur fait subir des pertes de rendement comprises entre 45 et 70%, résultant en des pertes financières de 1 à 2 millions de Francs CFA par hectare. Près de 80% des producteurs n’ont recourt qu’aux produits phytopharmaceutiques, dont seulement 42% sont homologués pour la tomate. Quinze substances actives sont utilisées, dont l’emamectine benzoate, l’acétamipride et la cyperméthrine. La résistance des populations aux pesticides est telle que de nombreux producteurs abandonnent des parcelles à cause d’infestations incontrôlables. Des méthodes alternatives sont parfois employées : destruction des plantes infestées, rotation de cultures, désherbage et biopesticides. Plusieurs producteurs pensent que l’invasion de cet insecte est indirectement la cause de conflits familiaux et de la baisse de leur niveau de vie.

Mots-clés : *Tuta absoluta*, tomate, insecticide, résistance, espèce invasive

Abstract:

Tuta absoluta is a leafminer native to South America and listed in Burkina Faso since 2016. Its larvae dig galleries in the leaves and fruits of the tomato. Through detailed surveys of 180 growers, we have assessed the impact of this pest on tomato production. The growers produce tomatoes on areas of less than ½ hectare. All of them have demonstrated their knowledge of *T. absoluta* and can describe its symptoms. On average, producers estimate that this leafminer causes yield losses of between 45 and 70%, resulting in financial losses of 1 to 2 million CFA francs per hectare. Almost 80% of producers use only plant protection products, of which only 42% are approved for tomatoes. Fifteen active substances are used, including emamectin benzoate, acetamiprid and cypermethrin. The resistance of the populations is such that many producers abandon plots because of uncontrollable infestation. Alternative methods are sometimes used: destruction of infested plants, crop rotation, weeding and biopesticides. This work is necessary to develop effective, accessible control methods that respect the environment and the health of producers.

Keywords: *Tuta absoluta*, tomato, insecticide, resistance, invasive species

1 Introduction

Tuta absoluta (Meyrick) (Lepidoptera : Gelechiidae) est une espèce de mineuse originaire d’Amérique du Sud où elle est considérée comme le principal ravageur de la tomate dans de nombreuses régions (Urbaneja et al., 2007). Ses larves causent des dégâts aux parties végétatives de la plante en se nourrissant du mésophylle des feuilles, ce qui entraîne une baisse de la capacité photosynthétique de la plante. Elles creusent également des galeries dans les bourgeons des jeunes tiges, les fleurs et les fruits (Desneux et al., 2010; Grissa-Lebdi et al., 2011). Les plantes de la famille des Solanacées sont les plus impactées, mais l’insecte peut aussi pondre et se développer sur d’autres espèces de Solanacées, ainsi que sur plusieurs plantes appartenant aux familles des Amaranthacées, Cucurbitacées, Convolvulacées, Fabacées, Euphorbiacées, Géraniacées, Malvacées et Astéracées (Bawin et al., 2016; Cherif & Verheggen, 2019).

Grâce à sa grande capacité de dispersion, évaluée à 800 km par an, *T. absoluta* est devenue le plus important ravageur de la tomate dans les pays européens et sud-américains. Depuis 2008, elle se répand rapidement sur le continent africain, particulièrement dans les pays du Maghreb, et a été découverte pour la première fois au Burkina Faso (région du Nord) en 2016 (Son et al., 2017a).

La surveillance du ravageur passe par la détection précoce de ses œufs, larves ou adultes. La lutte chimique reste la principale méthode pour réduire les dégâts de ce ravageur. Cependant, son comportement alimentaire endophyte le protège partiellement des insecticides. Cet insecte ayant une grande capacité de reproduction (jusqu'à 12 générations par an, >200 œufs/ par femelle), le développement de populations résistantes a rapidement été observé dans les nombreux pays où la lutte chimique non raisonnée a été pratiquée. Un large éventail de familles chimiques et de mode d'action sont concernés, incluant les Carbamates, les Organophosphorés, les Pyréthroïdes, les Néonicotinoïdes, les Spinosynes, les Avermectines et Milbémycines, les Pyrroles, les analogues de la Néréistoxine, les Benzoylurées, les Oxadiazines, les Semicarbazones, les Diamides et le Pyridalyl (Barati et al., 2018a; Campos et al., 2015a; Desneux et al., 2010; Grissa-Lebdi et al., 2011; Guedes et al., 2019; IRAC, 2020; Reyes et al., 2012; Roditakis et al., 2018; Silva et al., 2015; Siqueira et al., 2001; Siqueira et al., 2000a; Zibaee et al., 2018).

En conséquence, la présence d'infestations de *T. absoluta* peut conduire à l'anéantissement complet de la production ou la détérioration de la qualité commerciale des fruits par des dommages esthétiques et des pourritures (Desneux et al., 2010; EPPO, 2005).

Parmi les alternatives, les pièges à une phéromone (sexuelle) sont alors utiles pour la capture des premiers mâles (Caparros Megido et al., 2013b; Lobos et al., 2013). Des pièges lumineux (48 pièges. ha^{-1}) peuvent également être utilisés, mais avec une efficacité limitée. L'utilisation d'auxiliaires est possible mais reste la plupart du temps limitée aux serres et tunnels. Parmi ceux-ci on retrouve des prédateurs hémiptères (Miridae, Anthocoridae, Geocoridae, Nabidae et Pentatomidae) (Biondi et al., 2018; Desneux et al., 2010; Zappalà et al., 2013), des parasitoïdes d'œufs (Trichogramma spp) (Chailleux et al., 2012; Chailleux et al., 2013a) et de larves (Eulophidae et Braconidae) (Biondi et al., 2013; Ferracini et al., 2012).

Le contrôle microbien repose principalement sur des souches commerciales de *Bacillus thuringiensis* (Bt) var. kurstaki et aizawaii qui agissent par ingestion (González-Cabrera et al., 2011), mais des cas de résistances ont aussi été rapportés. Les nématodes (Steinernema et Heterorhabditis spp.) semblent aussi efficaces en conditions de laboratoire et de serre (Batalla-carrera et al., 2010; Biondi et al., 2018).

Au Burkina Faso, la tomate joue un rôle socio-économique et nutritionnel très important (MAH, 2011). Elle constitue le deuxième produit horticole après l'oignon. En 2017, elle représentait une superficie de 23.000 ha, pour une production estimée à plus de 200.000 tonnes durant la campagne 2016-2017 (MAAH, 2017).

Selon les données du dispositif du Comité inter-États de Lutte contre la Sécheresse au Sahel (CILSS) sur le suivi des flux transfrontaliers, environ 50 % de cette production est exportée, pour une valeur de 50 milliards de F CFA (76 247 135 Euros), vers les pays voisins notamment le Ghana et la Côte d'Ivoire (Bambio, 2018).

Ainsi, compte tenu de l'importance de la tomate pour le pays, du potentiel de nuisibilité de ce nouveau ravageur et des multiples plaintes des producteurs (Sawadogo et al., 2020b), nous avons souhaité évaluer la situation phytosanitaire en interrogeant les producteurs localisés à travers tout le pays.

2 Matériel et méthodes

Sites de l'étude - Pour évaluer l'impact phytosanitaire causé par l'invasion récente de *Tuta absoluta* en culture de tomates au Burkina Faso, nous avons mené des enquêtes auprès de 180 producteurs issus des principales communes productrices du pays : Dori et Baní dans la province du Séno (climat nord sahélien : pluviométrie < 500 mm/an, température quotidienne moyenne maximale > 39°C en campagne sèche) ; Ouahigouya, Thiou et Namissiguima dans la province du Yatenga (climat subsaharien : pluviométrie comprise entre 500-600 mm/an, température quotidienne moyenne maximale > 38°C en campagne sèche) ; Loumbila et Ziniaré dans la province de l'Oubritenga (climat Nord Soudanien, pluviométrie comprise entre 700-800 mm/an, température quotidienne moyenne maximale > 38°C) ; Kankalaba et Ouéléni dans la province de la Léraba (climat sud-soudanien, pluviométrie comprise entre 1000-1200 mm/an, température quotidienne moyenne maximale > 35°C) (WeatherSpark.com, 2020).

La figure 5 place les différents sites enquêtés sur la carte phytogéographique du Burkina Faso.

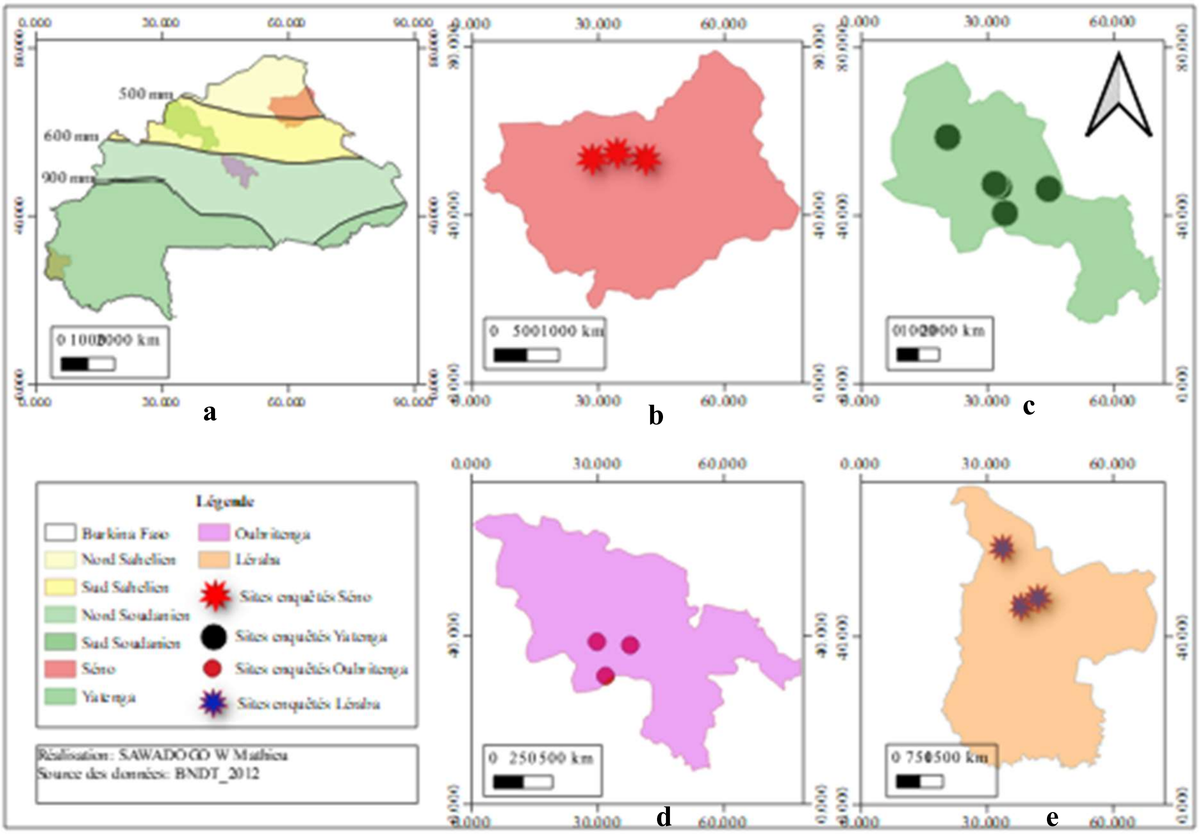


Figure 5 : Localisation des zones enquêtées

a : carte phytogéographique du Burkina avec les provinces enquêtées, b : carte du Séno avec les sites enquêtés, carte du Yatenga avec les sites enquêtés, carte de l'Oubritenga avec les sites enquêtés, carte de la Léraba avec les sites enquêtés.

Un questionnaire (voir annexe 1) a été élaboré et était constitué de 42 questions devant permettre de caractériser les exploitations de tomate, d'évaluer le niveau de connaissances des producteurs du ravageur et de lister les pratiques phytosanitaires qu'ils mettent en place pour y faire face. Nous avons aussi voulu évaluer les dégâts causés par ce nouveau ravageur et les pertes monétaires qui leur sont associées. Enfin, nous avons recueilli leurs suggestions quant aux mesures à prendre pour les aider à lutter contre ce ravageur.

Avant la réalisation des enquêtes, nous avons rencontré les agents d'encadrement des producteurs et les responsables des associations de producteurs des différents sites afin d'identifier les sites de production et les producteurs de tomate. Un choix aléatoire de 10 à 15 producteurs à enquêter par site a ensuite été réalisé. Les entretiens avec les producteurs se sont déroulés durant la période de février à septembre 2019, la plupart du temps au champ.

3 Résultats et discussion

3.1 Caractérisation des exploitations de tomate

La production de tomate dans les zones enquêtées reste l'apanage des hommes (98%) qui utilisent soit exclusivement la main d'œuvre familiale (61%), soit la main d'œuvre salariée (15%), les deux à la fois (19%) ou n'ont aucun recourt à une tierce personne (5%) dans leur exploitation.

La commercialisation des tomates est cependant réalisée par les femmes, qui ravitaillent les marchés locaux et exportent la tomate vers les pays voisins (CAPES, 2007). Les producteurs sont pour la plupart illettrés (36%), ou ayant le niveau de l'école primaire française (28%) ou du secondaire (12%). Certains sont instruits en arabe (14%) ou alphabétisés dans les langues nationales du Burkina Faso (10%). Le faible niveau d'éducation formelle des producteurs est un handicap pour la protection des cultures.

En effet, cette protection repose essentiellement sur l'utilisation de produits phytopharmaceutiques. Le mode d'emploi de ces produits est donc inaccessible pour la plupart des producteurs, qui ne peuvent pas prendre connaissance des doses recommandées, des délais avant récolte ou encore du type de nuisible ciblé par le produit (PDCA, 2019; Son et al., 2017b).

Cette situation entraîne des conséquences désastreuses incluant les échecs des traitements, le développement de populations résistantes, l'intoxication des hommes et des animaux, ainsi que la pollution de l'environnement (Haddi et al., 2017; Mirhosseini et al., 2019; Moradi et al., 2019; Roditakis et al., 2018).

En termes d'expérience dans la production de tomate, 36% des producteurs ont une expérience inférieure à 10 ans, 26% ont une expérience comprise entre 10 et 20 ans, 21% entre 20 et 30 ans et 11% entre 30 et 40 ans.

La production de la tomate se fait sur de petites superficies, typiquement inférieures à ¼ ha (47% des producteurs), ou comprises entre ¼ et ½ ha (32%), entre ¾ et 1 ha (17%) et plus d'un ha (4%).

Le tarissement précoce des points d'eau, les difficultés d'accès aux crédits agricoles et équipements d'irrigation performants et les méventes pourraient expliquer ces petites superficies (MAH, 2011). Des semences de variétés améliorées sont utilisées dans la majorité des cas (94%), le reste utilisant des variétés dites locales.

Les principales variétés utilisées sont Tropimech (44%), Mongal (43%), Cobra (39%), Petomech (25%) et Roman VF (3%). Si 94% des exploitants maraichers produisent des variétés améliorées, c'est avant tout parce que celles-ci sont prisées par les consommateurs. Par exemple, les variétés Tropimech et Petomech sont généralement préférées par les acheteurs étrangers parce que leurs fruits se conservent bien durant le transport.

La production des variétés Mongal et Cobra se justifie par leur tolérance aux nuisibles, mais aussi parce que ce sont des variétés adaptées à toutes les saisons et ayant un bon rendement (Technisem, 2016).

3.2 État de connaissances des producteurs sur *T. absoluta*

Compte tenu de son arrivée récente et rapide, et des dégâts qu'elle occasionne, tous les producteurs enquêtés connaissent *T. absoluta* et sont capables de décrire les symptômes qu'elle occasionne sur les différents organes de la plante.

La province du Yatenga serait l'un des premiers foyers à partir duquel le ravageur s'est propagé. En effet, 75% des enquêtés de cette province disent l'avoir rencontré pour la première fois dans leurs parcelles en 2013, alors que pour cette même date, seulement 4% et 2% des producteurs disent l'avoir observé dans l'Oubritenga et dans le Séno respectivement.

Sur base des témoignages provenant de la province de la Léraba, la mineuse n'y serait présente que depuis 2015. Il faut donc déplorer les faiblesses du système national de surveillance phytosanitaire, car en effet, les producteurs estiment que l'insecte était présent sur le territoire burkinabé au moins 3 années avant son annonce officielle de présence (Son et al., 2017a).

Ce système de surveillance est actuellement basé sur les alertes précoces des producteurs et des agents d'appui agricole, mais aussi sur les contrôles phytosanitaires dans les points d'entrée du pays, les prospections des agents chargés de la protection des végétaux et des chercheurs. Il semble important que ce dispositif de surveillance soit redynamisé pour éviter dans le futur d'autres événements d'invasion similaire (PDCA, 2019).

3.3 Pratiques phytosanitaires pour lutter contre *T. absoluta*

Puisque 77% des producteurs n'ont jamais reçu de formation en protection des cultures, 80% d'entre eux n'ont recourt qu'aux pesticides chimiques de synthèse comme seul moyen de lutte contre *T. absoluta*. L'utilisation systématique des pesticides expliquerait une méconnaissance de l'entomofaune de la tomate (bio agresseurs et auxiliaires) et des moyens de lutte alternatifs efficaces et respectueux de l'environnement par les producteurs (Son et al., 2018).

Plusieurs pulvérisations sont réalisées au cours du cycle de production de la tomate. Ainsi 42% des producteurs réalisent moins de 10 traitements, 25% réalisent entre 10 et 20 traitements phytosanitaires, 12% réalisent entre 20 et 30 pulvérisations et 17% entre 30 et 40 pulvérisations. Cette utilisation répétée des pesticides explique leur actuelle relative inefficacité. Cela se traduirait par une méconnaissance du pesticide adéquat à utiliser en fonction du ravageur (Son et al., 2017b) mais aussi par l'acquisition de résistance des bio agresseurs vis-à-vis des pesticides (Guedes et al., 2019).

Dans l'ensemble, environ 1/3 de ces traitements sont annoncés par les producteurs comme spécifiquement réalisé pour la lutte contre *T. absoluta*. En effet, ce ravageur invasif n'est pas aisé à combattre, compte tenu de sa grande capacité de reproduction, sa stratégie alimentaire et sa résistance avérée à plusieurs molécules. Ainsi, plusieurs cas d'abandon de parcelles de production suite aux attaques de *T. absoluta* ont été constatés à travers le pays (Sawadogo et al., 2020b). Seuls 42% de ces produits sont effectivement homologués pour la protection de la plante de tomate, 34% sont homologués pour protéger le cotonnier, 4% sont homologués pour protéger d'autres spéculations. Les 20% de produits restant utilisés par les producteurs en lutte contre *T. absoluta* n'ont aucune homologation (figure 6).

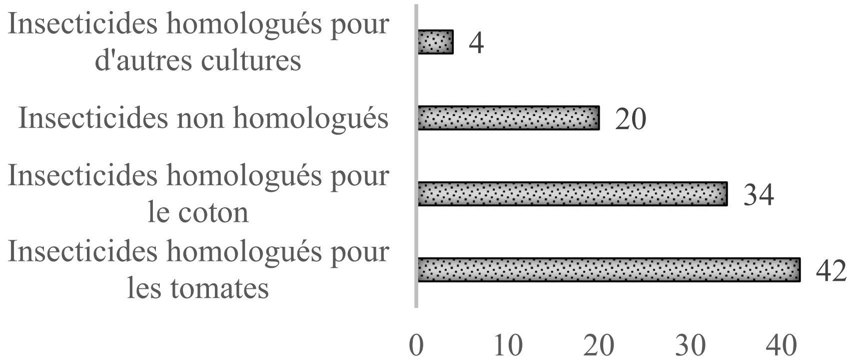


Figure 6 : Types d'homologations des insecticides utilisés pour lutter contre *T. absoluta*

Les pesticides destinés à protéger le cotonnier sont généralement plus concentrés que ceux homologués pour le maraichage traduisant ainsi leurs meilleures efficacités (CSP, 2019). Aussi, leurs disponibilités même dans les zones non cotonnières expliquent leurs fortes utilisations.

L'usage de produits non homologués s'expliquent par leurs coûts qui sont relativement plus faibles que ceux homologués (absence de toute taxe car ce sont des produits issus de la fraude).

Quinze molécules actives utilisées contre *T. absoluta* ont été identifiées au cours de cette enquête (figure 7) : l'emamectine benzoate (25% des produits utilisés), l'acétamipride (19%), la cyperméthrine (18%), le Lambda-cyhalothrin (12%), le profénofos (8%), l'abamectine (5%), l'indoxacarbe (4%), l'imidacloprid (3%), le methomyl (2%) et les 4% restants sont la deltamétrine, le chlorfluazuron, le pyriproxyfen, le beta-cyfluthrin, le chlorpyrifos et du *Bacillus thurengensis*.

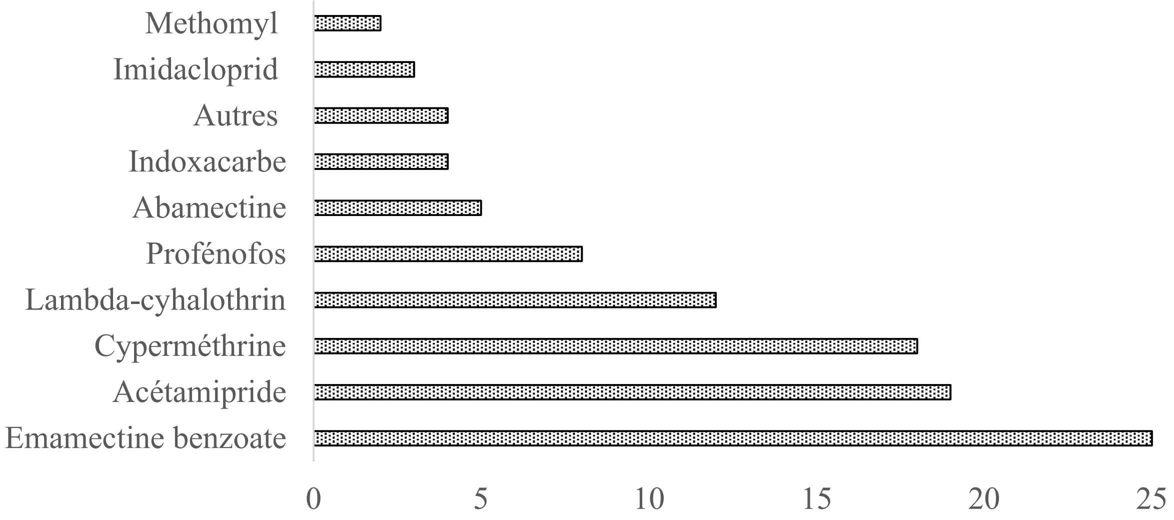


Figure 7 : Proportion (%) des molécules utilisées dans la lutte contre *T. absoluta*

Certains producteurs affirment même qu'ils mélangent jusqu'à cinq produits différents pour réaliser les traitements contre ce ravageur. Plusieurs producteurs nous ont confié que certains de leurs traitements s'étaient avérés inefficaces au point devoir abandonner leurs champs à cause de populations de *T. absoluta* incontrôlables.

Une évaluation de la probabilité d'échec de traitement (PET) de molécules comme l'abamectine, le spinosad, le chlorpyrifos, le *Bacillus thuringiensis*, l'acétamipride, la cyperméthrine, le λ- cyhalothrin et la deltaméthrine sur des populations de *T. absoluta* du Burkina Faso, montre que les trois premières molécules ont des PET nulles, et pourraient mieux contrôler ce ravageur (Sawadogo et al., 2020b).

À côté de ces 80% de producteurs qui n'ont recourt qu'aux produits phytopharmaceutiques, 20% des producteurs utilisent une combinaison de produits phytopharmaceutiques et de méthodes de lutte alternatives. Parmi celles-ci on retrouve l'arrachage et la destruction des organes/plantes infestées (49%) en pépinière, le désherbage (37%), la rotation de la culture de tomate avec d'autres spéculations (31%), et l'utilisation de biopesticides (20%). La lutte contre les adventices se faisant manuellement avec la houe, cette pratique pourrait présenter l'avantage supplémentaire de permettre de remuer également la terre et ramener en surface les chrysalides enfouies dans le sol et les exposer aux rayons solaires et à d'éventuels prédateurs (Germain et al., 2009).

Pour les rotations, les spéculations utilisées sont les Liliaceae (*Allium cepa* L.), Solanaceae (*Solanum tuberosum* L., *Solanum melongena* L., *Capsicum annuum* L., *Solanum aethiopicum* L., *Solanum macrocarpon* L., *Capsicum chinense* Jacq.), Asteraceae (*Lactuca sativa* L.), Brassicaceae (*Brassica oleracea* L.), Fabaceae (*Phaseolus vulgaris* L., *Phaseolus coccineus* L., *Vigna unguiculata* (L.) Walp., *Vigna subterranea* (L.) Verdc., *Arachis hypogaea* L.), Cucurbitaceae (*Cucumis sativus* L., *Cucumis melo* L., *Cucurbita pepo* L., *Citrullus lanatus* (Thunb.) Matsum. & Nakai.), Lamiaceae (*Mentha* L. spp), Malvaceae (*Abelmoschus esculentus* (L.) Moench), Polygonaceae (*Rumex* L. sp), Chenopodiaceae (*Amaranthus* L. sp, *Spinacia oleracea* L.), Poaceae (*Zea mays* L, *Oryza sativa* L., *Sorghum bicolor* (L.) Moench), Apiaceae (*Daucus carota* L) et Convolvulaceae (*Ipomoea batatas* (L.) Lam.).

La rotation culturale pourrait être une stratégie efficace (Cherif & Verheggen, 2019), mais ne pourra produire de bons résultats que si elle est mise en œuvre à l'échelle d'un périmètre maraicher et qu'elle n'implique pas de plantes hôtes (Biondi et al., 2018; Desneux et al., 2010). Les biopesticides (extraits aqueux et huiles essentielles) sont de plus en plus proposés pour la lutte contre les nuisibles de la tomate (Isman, 2006). Cependant, même s'ils ont l'avantage d'être moins toxiques pour l'environnement et les organismes non cibles, leur complexe formulation et la lenteur de leur action sont des contraintes qui limitent leurs utilisations. Même si les producteurs ne comptent pas sur l'action des organismes auxiliaires pour contrôler les populations de *T. absoluta*, certains affirment que les araignées, les crapauds, les oiseaux granivores, les fourmis et les mantes religieuses sont des prédateurs de *T. absoluta* dans leurs champs.

Lors de nos prospections nous avons découvert *Nesidiocoris tenuis* un prédateur de *T. absoluta* (Sawadogo et al., 2020b). Ces auxiliaires pourraient mieux contribuer à la lutte contre les ravageurs notamment *T. absoluta* si moins de pesticides étaient utilisés et que des stratégies permettant leurs conservations et leurs proliférations dans les champs de tomate étaient développées.

La principale plante hôte de *T. absoluta* est la tomate. Cependant, cet insecte pouvant également se développer sur d'autres plantes, potentiellement présentes à proximité de la zone de production de tomate (Cherif & Verheggen, 2019). Ainsi, au cours de nos enquêtes, nous avons constaté que l'utilisation d'Abamectine dans certains sites de production (à Thiou principalement) avait pour conséquence que les adultes de *T. absoluta* quittaient les parcelles de tomate et colonisaient les plantes sauvages (comme l'Amaranthus sp.) où aucun traitement n'est appliqué. Ces plantes fonctionnent alors comme un réservoir de ravageurs pour de futures infestations.

3.4 Estimation des dégâts

Les dégâts causés par *T. absoluta* sur les feuilles de tomate semblent être plus sévères dans les sites de la province de l'Oubritenga où 100% des producteurs estiment que plus de 50% de la végétation de leur champ est détruite par ce ravageur à partir de la première récolte de tomate. Le même degré de sévérité est atteint pour 62% des producteurs dans le Séno, 45% dans la Léraba et 41% dans le Yatenga.

Cette disparité de sévérité par zone de production, pourrait s'expliquer par l'efficacité des principales molécules utilisées (Sawadogo et al., 2020b), l'alternance des pesticides à modes d'actions différents d'une campagne à l'autre (pour éviter la survenue de résistance dans une localité) (IRAC, 2020) et dans les bonnes pratiques d'utilisations des pesticides par les producteurs.

Même si certains producteurs affirment avoir pratiquement tout perdu avec l'invasion de *T. absoluta*, il ressort qu'en moyenne les producteurs estiment avoir perdu 58.8±23.3% par rapport à ce qu'ils gagnaient avant l'arrivée de ce ravageur. Mais cette impression est variable entre les provinces : 46.3±20.8% dans le Yatenga, 56.7±23.3% dans la Léraba, 58.6±20.2% dans l'Oubritenga et 70.2±22.8% dans le Séno.

Les perceptions de perte de productions sont plus élevées dans le Séno. Cela pourrait s'expliquer par les fortes températures (climat nord sahélien) qui sévissent dans cette localité. En effet, les fortes températures sont caractérisées par des cycles de *T. absoluta* plus courts (Martinou et al., 2014). Ainsi, on aurait plus de générations du ravageur (augmentation exponentielle de population) au cours d'une campagne de production dans cette localité que dans les autres.

Dans ces zones de production, les producteurs s'attendaient à des rendements de 18.806±5.846 kg.ha^{-1} dans le Séno, 13.252±5.077 kg.ha^{-1} dans la Léraba, 20.706± 6.746 kg.ha^{-1} dans l'Oubritenga et 18.053± 6.176 kg.ha^{-1} dans le Yatenga, en l'absence de *T. absoluta*. Ces rendements sont faibles par rapport au potentiel de 28 à 45 tonnes des variétés produites au Burkina Faso (MRSI, 2014).

Quant aux pertes liées à la destruction des fruits (due aux symptômes et malformations les rendant impropres à la vente), elles semblent plus élevées dans l'Oubritenga et dans le Yatenga (avec 33.5 ± 25.2% et 26.6 ± 18.4% respectivement), que dans le Séno et la Léraba (12.2 ± 22.1% et 12.3 ± 23.4%, respectivement) (figure 8 A).

Cette perception pourrait être liée aux exigences des marchés de destination de ces produits. En effet, la tomate de l'Oubritenga du Yatenga est plutôt destinée à l'exportation vers d'autres pays et à la capitale Ouagadougou. Les productions du Séno et de la Léraba sont quant à elles destinées à la consommation locale généralement moins exigeante.

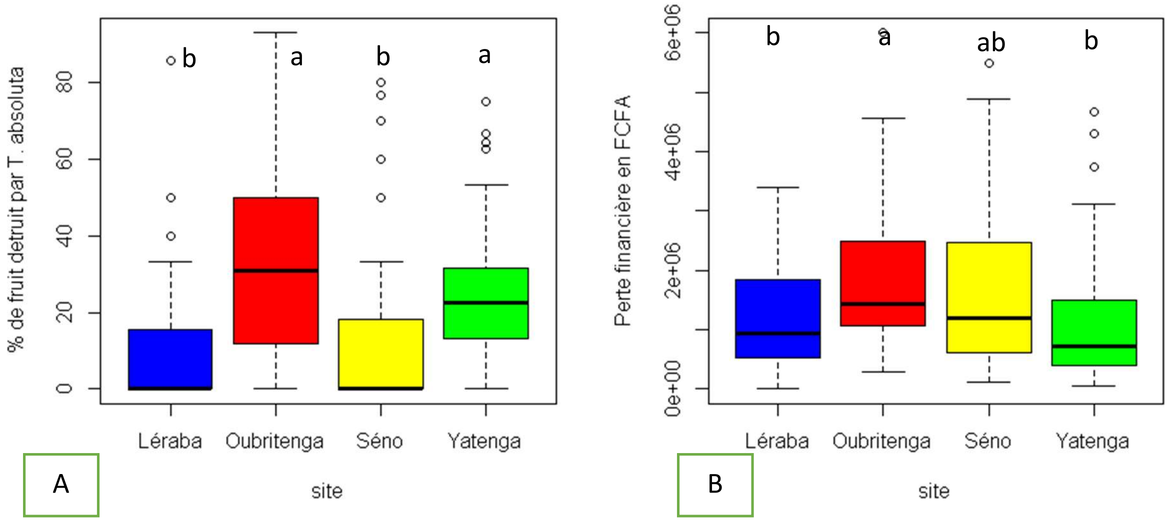


Figure 8 : Proportion (%) de fruits détruits (A) et Perte financière par ha (B).

Les boxplots avec la même lettre ne diffèrent pas significativement les uns des autres au seuil de 5 % selon le test de « Kruskal-Wallis ».

3.5 Conséquences liées à l'invasion de *T. absoluta*

Sur base des pertes de rendements estimées, les producteurs ont pu calculer les pertes financières associées (figure 8B). Ces pertes estimées montent à 1.895.825 ± 1.273.507 F

CFA.ha^{-1} et 1.694.542 ± 1.373.625 F CFA.ha^{-1} dans l'Oubritenga et le Séno, respectivement. Elles seraient plus basses dans le Yatenga (1.176.827±1.148.281 F CFA.ha^{-1}) et la Léraba (1.176.740±849.338 F CFA.ha^{-1}).

Ces pertes causées par *T. absoluta* conduisent 67% des producteurs à affirmer qu'ils n'ont pas généré de bénéfices au cours de l'année écoulée. Ces pertes pourraient s'expliquer non seulement par l'augmentation du coût de production lié à la nécessité de développer et d'appliquer de nouvelles stratégies de contrôle du ravageur mais aussi à la diminution de la quantité de productions commercialisables (Sannino & Espinosa, 2010).

Les conséquences économiques et sociales dans ces cas peuvent être désastreuses (CABI, 2020). Ainsi, plusieurs ont éprouvé des difficultés à payer leurs employés, honorer le remboursement des fonds de roulement, payer la location de leurs parcelles de production et payer les crédits intrants qu'ils ont contractés avec les commerçants et les institutions de microfinance.

Certaines familles sont tombées en insécurité alimentaire et dans l'incapacité de se soigner car c'est l'argent issu de la vente de la tomate qui leur permettait d'acheter les vivres pour se nourrir pendant les périodes de soudure, mais aussi de se soigner.

Des problèmes sociaux tels que l'incapacité d'honorer les frais de scolarité des enfants, de se marier, de terminer une construction de maison ou d'acheter une mobylette ont été évoqués.

Plusieurs producteurs pensent que l'invasion de cet insecte est indirectement la cause de conflits familiaux et de la baisse de leur niveau de vie.

L'abandon des parcelles de production suite au découragement, amène certains producteurs à dire que pour qu'ils puissent reprendre la production de tomate, il leur faudra nécessairement de l'aide. Une solution alternative avancée est celle de la migration vers une autre localité, pour se refaire une santé financière avant de revenir.

L'endettement semble la seule solution pour poursuivre la production dans des conditions inchangées. Certains estiment même que si aucune solution n'est trouvée pour ce ravageur, ils réduiront considérablement les superficies dédiées à la tomate, ou abandonneront définitivement cette production.

Enfin, quelques producteurs pratiquent le séchage des tomates qui ont été blessées par *T. absoluta*. Si le séchage permet de masquer les symptômes, la tomate séchée n'est malheureusement pas prisée par le consommateur burkinabè (CAPES, 2007).

3.6 Mesures d'accompagnement reçues par les producteurs après l'invasion de *T. absoluta* et suggestions de ces derniers

Les producteurs se sentent abandonnés depuis l'établissement de ce nouveau ravageur au Burkina Faso. En effet, 93% d'entre eux affirment n'avoir reçu aucun soutien (technique, matériel ou financier) pour lutter contre ce ravageur. Le reste des producteurs affirment avoir reçu du soutien matériel et financier de leur famille, de projets et ONG et des autorités administratives.

Compte tenu de l'arrivée récente de ce ravageur, même les agents chargés de l'encadrement des producteurs méconnaissent les stratégies efficaces de lutte, si bien qu'ils n'arrivent pas à apporter l'appui technique nécessaire aux producteurs.

Une mise à niveau des connaissances de ces derniers est donc nécessaire d'autant plus que les producteurs estiment avoir besoin d'un appui technique en termes de formation en lutte intégrée contre les nuisibles des cultures, et notamment *T. absoluta*.

Ils souhaitent pouvoir disposer de bio-insecticides et d'insecticides de synthèse efficaces et bon marché. Ils ont besoin d'un appui matériel, comprenant des pulvérisateurs performants et en équipements de protection individuelle. Ils recommandent que des suivis techniques rapprochés soient menés par les spécialistes de la protection des végétaux. Ils sont convaincus que des efforts doivent être déployés par leur gouvernement pour soutenir la recherche, particulièrement pour mettre en place des solutions de lutte contre ce ravageur.

4 Conclusion

Tuta absoluta sévit dans toutes les zones agroécologiques du Burkina Faso et cause d'énormes dégâts à la production de tomate. L'utilisation d'insecticides de synthèse reste le moyen privilégié par les producteurs malgré les nombreux échecs de traitements enregistrés dans plusieurs cas. Nous recommandons que des efforts financiers soient déployés pour soutenir la recherche et plus particulièrement le développement de méthodes de lutte contre ce ravageur qui soient à la fois efficaces, respectueuses de l'environnement et de la santé des utilisateurs, tout en étant abordables financièrement.

Partie III : Phénologie et modes de reproduction de *Tuta absoluta* au Burkina Faso

L'explosion démographique et la survie des insectes sont fortement liées aux conditions environnementales, entre autres à la température, à l'humidité relative de l'air et à la présence d'agents de contrôle. Ainsi, identifier les périodes d'abondance des populations de mineuse de la tomate est essentiel à tout développement de stratégie de lutte. Ceci nous a conduit à suivre la dynamique des populations de *T. absoluta* pendant deux années dans des zones climatiques très contrastées (climat Sub-Saharien et climat Sud-Soudanais).

De même, la littérature rapporte que *T. absoluta* peut se reproduire par parthénogenèse deutérotoque (production de mâles et de femelles à partir de femelles non fécondées), mais aussi que ce mode de reproduction pouvait être annulé par une infestation naturelle de bactéries *Wolbachia*. Nous avons donc mesuré la capacité des populations du Burkina Faso à se multiplier par parthénogenèse.

Ces informations relatives à la phénologie et aux modes de reproduction nous permettent de discuter de la pertinence de l'utilisation des phéromones sexuelles dans les stratégies de lutte par annihilation des mâles de *T. absoluta*.

Chapter III.1

Population dynamics of the tomato leafminer *Tuta absoluta* Meyrick in sub-Saharan and South Sudanese climates

Chapter III. 1 : Population dynamics of the tomato leafminer *Tuta absoluta* Meyrick in sub-Saharan and South Sudanese climates

This chapter is an adapted version of the article

Wendnéyidé Mathieu SAWADOGO, Irénée SOMDA, François J. VERHEGGEN (under revisions). Population dynamics of the tomato leafminer *Tuta absoluta* Meyrick in sub-Saharan and South Sudanese climates. Phytoparasitica

Abstract

The South American tomato pinworm, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), is an invasive insect species newly established in West Africa where it has become the main threat to the tomato industry. This study aims at describing the phenology of this pest, to help better identify outbreak periods and adapt current control strategies. Using pheromone traps, we monitored the population dynamics of *T. absoluta* over a two years period, in two tomato-producing regions of Burkina Faso, experiencing contrasting climatic conditions.

T. absoluta is present throughout the year in the country. Their populations are typically lowest during the rainy season (June-September) and highest during the warm season (March-April). The peak of pest density was reached in March, simultaneously in both regions, while most tomato plots are at fruit maturity stage. However, in the Region of Ouahigouya (sub-Saharan climate), where the annual mean temperature is higher and the cold season shorter, *T. absoluta* were up to six times more abundant than in Bobo-Dioulasso (South Sudanese climate), reaching over 6000 individuals per trap and per week.

We discuss the potential management strategies that should be implemented, including the period of the year tomato should be produced according to the specific climatic conditions of each region. We also discuss the importance of using pheromone-based monitoring traps as well as their potential in a male-mass trapping strategy.

Keywords: Integrated pest management, population dynamics, crop protection, semiochemicals.

1 Introduction

The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is a worldwide pest of Solanaceae, especially tomato (Biondi et al., 2018; Germain et al., 2009; Sawadogo et al., 2020a). After invading Europe (Urbaneja et al., 2007), it reached Burkina Faso in 2016 (Son et al., 2017a) where it inflicts huge losses on tomato producers (Sawadogo et al., 2020a). Caterpillars devour all aerial parts of the plant, digging mines in leaves, fruits, flowers, terminal buds and tender stems (Desneux et al., 2010). The pest has a high reproductive capacity: 10 to 12 generations per year and over 250 eggs per female (Fernandez & Montagne, 1990; Germain et al., 2009; Uchoa-Fernandes et al., 1995). Several sustainable management methods have been recently developed, including tolerant cultivars, physical barriers, cultural practises, beneficials, entomopathogens, and pheromones for male annihilation or mating disruption (Abd El-Ghany et al., 2018; Dammak et al., 2015; Gharekhani & Salek-Ebrahimi, 2014a; Han et al., 2019b; Jallow et al., 2020; Nannini et al., 2012; Perez-Hedo et al., 2021; Sohrabi et al., 2016; Zarei et al., 2019). But these methods remain inaccessible to local farmers, who have to apply insecticidal treatments in their tomato plots since *T. absoluta* invasion (Guedes et al., 2019; Sawadogo et al., 2020b).

A better knowledge of the population dynamics of this pest would make it possible to make predictions of its periods of outbreaks and would pave the way to a more reasoned chemical control (Abbes & Chermiti, 2014; Tonnang et al., 2015). The population dynamics of *T. absoluta* can be influenced by the topography of the environment (altitude, latitude, presence of physical barriers such as forests, mountains, water tendencies...), winds (Gontijo et al., 2012; Guedes & Siqueira, 2012), air temperature and humidity (Desneux et al., 2010; Han et al., 2019b; Marouelli et al., 2013). For these reasons, it can vary greatly from one locality to another.

In this study, we aim at describing the periods of abundance of the leafminer in two production zones characterised by contrasting climatic conditions. To this end, we monitored the population dynamics of *T. absoluta* in Ouahigouya (sub-Saharan climate) and Bobo-Dioulasso (southern Sudanese climate) during a two-years period.

2 Materials and methods

2.1 Monitoring regions

Two monitoring locations were selected based on their contrasted climate and tomato producing habits (Figure 9): (1) the Somyaga production site in the town of Ouahigouya, located in the province of Yatenga, in the North region; (2) and the Tolotama production site in the town of Bobo-Dioulasso, located in the province of Houet, in the Hauts Bassins region. There are two main production seasons in these sites: the rainy season (May-September) and the dry season (October-April). As the crops are not planted at the same time by the producers, tomato production plots can be found almost all year round in these two sites. The climatic characteristics differ at both monitoring sites (detailed on www.WeatherSpark.com):

- Bobo-Dioulasso is characterised by a hot season lasting 2.5 months, from 21 February to 5 May, with an average daily high temperature above 35.5°C and a cold season of 2.5 months, from 5 July to 21 September, with an average daily high temperature below 30.5°C. The coldest day of the year is January 1, with an average low of 19.4°C and a high of 31.7°C. The wettest season lasts 4.9 months, from 9 May to 5 October, while the driest season lasts 7.1 months, from 5 October to 9 May. The relative humidity is only above 25% for 7.7 months, from 24 March to 14 November, reaching a saturation point on 19 August, with a relative humidity of 100%.
- In Ouahigouya, the hot season lasts 2.3 months, from 21 March to 29 May, with an average daily high temperature above 38.3°C. The cold season lasts 1.6 months, from 12 December to 31 January, with an average daily high temperature below 32.8°C. The coldest day of the year is January 3, with an average low of 17.8° C and a high of 31.1°C. It rains for 3.4 months, from 11 June to 24 September, and the driest season lasts 8.6 months, from 24 September to 11 June. Relative humidity is above 25% for only 6.0 months, from 28 April to 27 October.

2.2 Monitoring method

Tuta absoluta was monitored continuously for 24 months, starting from February 2019 and ending in February 2021.

In both monitoring sites, we placed four Tutasan® traps associated with a capsule releasing the female sex pheromone (Biobest, Belgium) in tomato production plots (figure 10 A). Each trap was filled with soapy water so that the male adults of the leaf miner drown in it. The number of individuals caught in the trap (figure 10 B) was counted every 3 days during two years, and the soapy water was renewed when needed. The pheromone lure was renewed every 5 weeks, as recommended by the manufacturer.

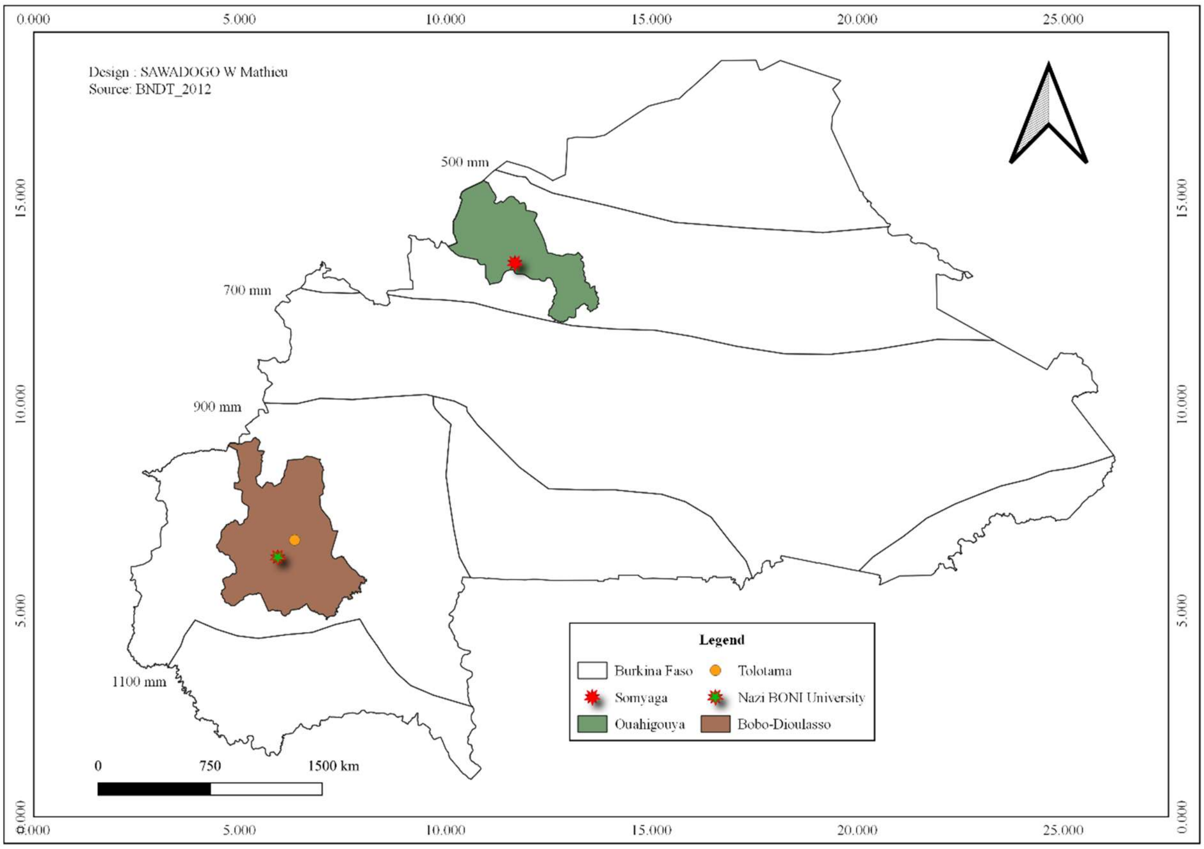


Figure 9: Areas for monitoring *T. absoluta* population dynamics

Figure 10 : Piège à eau couplé à la phéromone (A) et capture de *T. absoluta* de 3 jours (B)

2.3 Statistical analyses

The data were first tested for normality using the Shapiro-Wilk test. The analysis of variance test (ANOVA) and the non-parametric Kruskal Wallis test were used to compare the population dynamics of the different months according to whether they follow a normal distribution or not. The comparison of two-by-two rankings of the means was carried out by Dunn's method (at the 5% level of significance) for the non-parametric tests and the Student-Newman-Keuls method for the analysis of variance. The various statistical tests and the graph were carried out with XLSTAT 2016. The map was made with QGIS3.10.

3 Results and Discussion

T. absoluta is present throughout the year in the country with the lowest frequencies recorded in August (21.2±16.5 adults/trap.week) in Bobo-Dioulasso and in September (85.1±15.2 adults/trap.week) in Ouahigouya (Figure 11). The peak density of the pest was reached in March, simultaneously in both regions. However, *T. absoluta* was up to six times more abundant in Ouahigouya than in Bobo-Dioulasso (6418±959 and 991±439 adults/trap.week, respectively). Several environmental and meteorological factors influence *T. absoluta* population dynamics (Gontijo et al., 2012; Marouelli et al., 2013), we discuss them below.

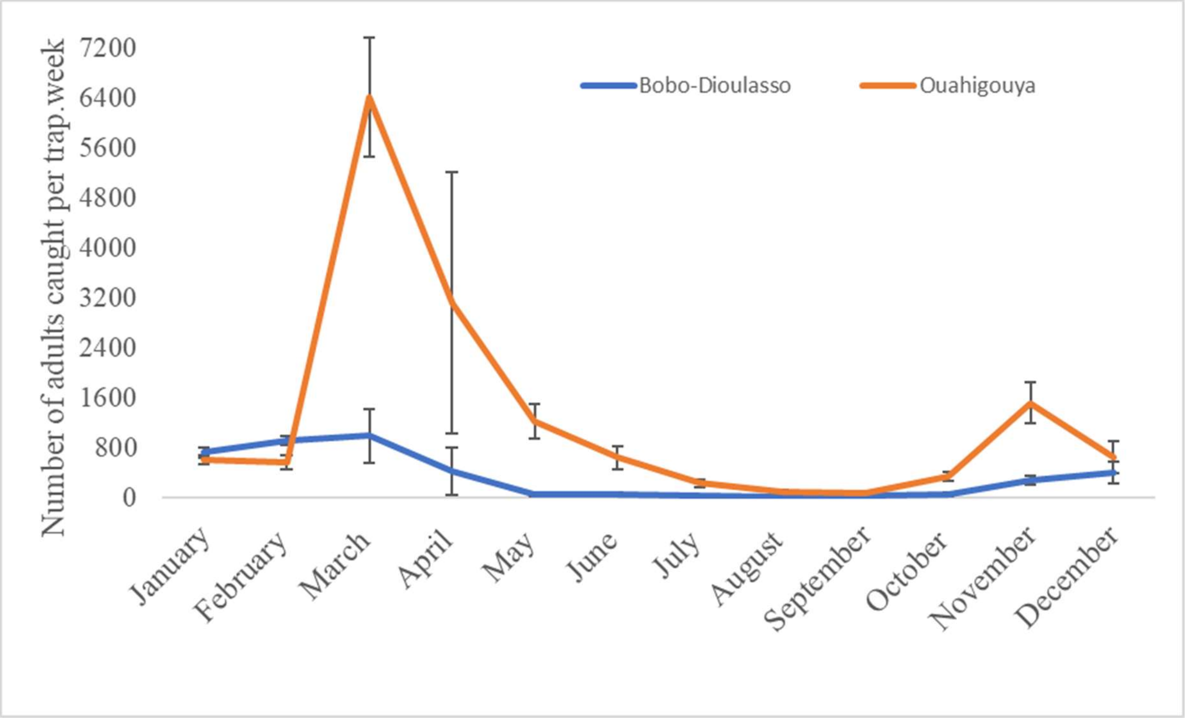


Figure 11: Evolution of *T. absoluta* adult catches from two locations of contrasted climatic conditions.

In both regions, the lowest frequencies of capture were recorded in August and September, when the rainfalls are the most important (between 202 and 313 mm of water in Bobo-Dioulasso and between 119 and 273 mm in Ouahigouya). Rainfall is an important factor in the seasonal mortality of *T. absoluta*: through splashing or runoff, rain can detach and carry away eggs, larvae that are outside the galleries and pupae that are not well buried in the soil (Bacci et al., 2019; Wakisaka et al., 1992, 1991). They could reduce the survival rate of larvae by 36% (de Medeiros et al., 2010). The rainy season is also the most favourable for natural enemies (Bacci et al., 2019; Biondi et al., 2018; Wakisaka et al., 1992). Except for the period December-February, the number of captures in Ouahigouya was higher than in Bobo-Dioulasso. In Ouahigouya, the mean annual temperature is higher and the cold season is shorter. The Bobo-Dioulasso region is characterized by more important rainfalls (1000 mm) than Ouahigouya region (780 mm). Following the findings of Chermiti & Abbes, 2012 who found a drastic reduction in *T. absoluta* catches after a rain, one could understand the higher catches in Ouahigouya than in Bobo-Dioulasso during the rainy season.

Higher catch frequencies were recorded during the dry period in both regions. Catches increased with the increase in temperature observed from December to March. The impact of temperature on the life cycle of the tomato leafminer is well described: higher temperature allow faster development and higher reproductive rate (Barrientos et al., 1998; Cuthbertson et al., 2013). The lengthening of the development cycle could result in a reduction in the number of generations per year and a greater predisposition of the insect to be killed either by a natural enemy or by insecticides (Siqueira et al., 2000a). Consequently, the difference in the number of captures between Bobo-Dioulasso and Ouahigouya can be partly explained by the difference in temperature: Bobo-Dioulasso is subjected to a sub-Sudanese climate, with lower mean temperatures, while Ouahigouya experiences a sub-Saharan climate.

Another factor affecting *T. absoluta* populations is the period of tomato transplanting. The first tomato transplanting occurs at the beginning of the rainy season, specifically in June and July. Consequently, a decrease in the frequency of captures was observed, especially in Ouahigouya: the population dropped from 649±186 (in June) to 85±15 adults/trap.week (in September). In both regions, the period of fruit maturation -September to October- coincided with a lower frequency of pests, compared to the rest of the year (K=77.97, p-value< 0.0001 at Bobo-Dioulasso; K=85.96, p-value< 0.0001 at Ouahigouya). During the dry season, transplanting occurred over a wider period: from October to February. Consequently, mature fruits produced during the dry season were more subject to *T. absoluta* infestations than fruits maturing between September and October (rainy season). Over the period of December to February, between 402±167 and 917±64 adults/trap.week were caught in Bobo-Dioulasso, and between 565±111 and 650±263 adults/trap.week in Ouahigouya.

Knowledge of the bioecology of *T. absoluta* is a crucial factor for the development of control strategies (Biondi et al., 2018). Thus, the determination of favourable periods for the development of the pest could allow the determination of a cropping calendar capable of avoiding periods of very high outbreaks (Abd-Elgawad, 2014). In view of the above, the periods favourable to the proliferation of the leafminer must be considered in the development of tomato cropping calendars. It would therefore be wise to schedule tomato cultivation during the rainy season or to start production very early in September or October for dry season production in order to avoid the hot periods of the year when the leafminer is most prolific.

Chapter III.2

Comparison of the fertility of virgin and mated females of the tomato leafminer, a parthenogenetic moth species

Chapter III.2: Comparison of the fertility of virgin and mated females of the tomato leafminer, a parthenogenetic moth species

This chapter is an adapted version of the article

Wendnéyidé Mathieu SAWADOGO, Schémaéza BONZI, Besmer Régis AHISSOU, Irénée SOMDA, Anne LEGRÈVE & François VERHEGGEN (under revisions). Comparison of the fertility of virgin and mated females of the tomato leafminer, a parthenogenetic moth species. Journal Applied of Entomology

Abstract

The tomato leafminer is a worldwide pest of tomato. Among the control strategies currently deployed lies males' annihilation, even though the species practices a deuterotokous parthenogenesis. Here, we compared the fertility of virgin and mated females over two generations, as well as additional life history traits. Virgin females had a longer lifespan (9.8 ± 3.4 days) than mated ones (6.8 ± 3.1 days) (P=0.001). They also laid fewer eggs (10.1 ±11.1 eggs/female) than mated females (57.4 ± 34.5 eggs/female) (P<0.001) and over a longer period of time: most of their eggs were laid after 6 days of life (80%), whereas mated females laid 83% of their egg load in less than 5 days. Deuterotokous parthenogenesis was observed on each virgin female, and as many males and females were counted from their offspring (P=0.83). Also, virgin females laid as many eggs (5.3±4.6 eggs/female) as their virgin mothers (p=0.08). We discuss the significance of these results as regard to pheromone-based control strategies.

Keywords: Deuterotokous parthenogenesis, annihilation technique, *Tuta absoluta,* sex pheromones

1 Introduction

Since the 1950s, the South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is considered one of the major pests of tomato in South America (Biondi et al., 2018; Estay, 2000). Male annihilation lies among the available methods of control: sex pheromone is applied for early detection of the pest but also to massively trap males using water, sticky or light traps, associated or not with an insecticide (Chidege et al., 2018; Cocco et al., 2013; Jallow et al., 2020; Michereff-Filho et al., 2000). Unfortunately, their use could be compromised by the reproductive mode of *T. absoluta*. Indeed, the existence of deuterotokous parthenogenetic reproduction has been discovered under laboratory conditions in French, Tunisian and UK populations of the leafminer (Abbes and Chermiti, 2014; Caparros Megido et al., 2012; Grant et al., 2021). This form of parthenogenetic reproduction assumes that virgin females lay eggs that produce both male and female individuals as opposed to thelytokous (females produced from unfertilized eggs) and arrhenotokous (males produced from unfertilized eggs) parthenogenesis, all three types of which are found in *Thrips tabacci* (Thysanoptera: Thripidae) (Nault et al., 2006).

Unlike other parthenogenetic species, notably *Callosobruchus maculatus* (Coleoptera: Chrysomelidae) (Amiri & Bandani, 2021), F1 individuals born from virgin females can also perform parthenogenesis and potentially rebuild a new population after the application of a male annihilation strategy (Abbes & Chermiti, 2014). The parthenogenesis deuterotokous would be incompatible with the infestation of the insect by Wolbachia bacteria and would not be influenced by temperature (Carvalho et al., 2018; Nault et al., 2006).

However, it is unclear whether the reproductive capacity of a parthenogenetic *T. absoluta* population decreases compared to a population where copulation frequently occurs. In this study, we compared the fertility, as well as other life history traits, of virgin and mated females originating from two *T. absoluta* populations located in contrasted agro-climatic zones of Burkina Faso, a newly invaded area.

2 Materials and Methods

About 400 insects (F0) were collected as larvae in two regions of Burkina Faso: Ouahigouya (Somyaga) and Bobo-Dioulasso (Kuinima) and brought to the laboratory. Insects from both populations were kept in separated cages and were allowed to reproduce on tomatoes (v. Mongal) inside net cages. Their offspring (later called F1) were then collected as pupae and sexed based on the terminal part of the abdomen, following the method described by Coelho & França, 1987 and Genç, 2016 (figure 12).

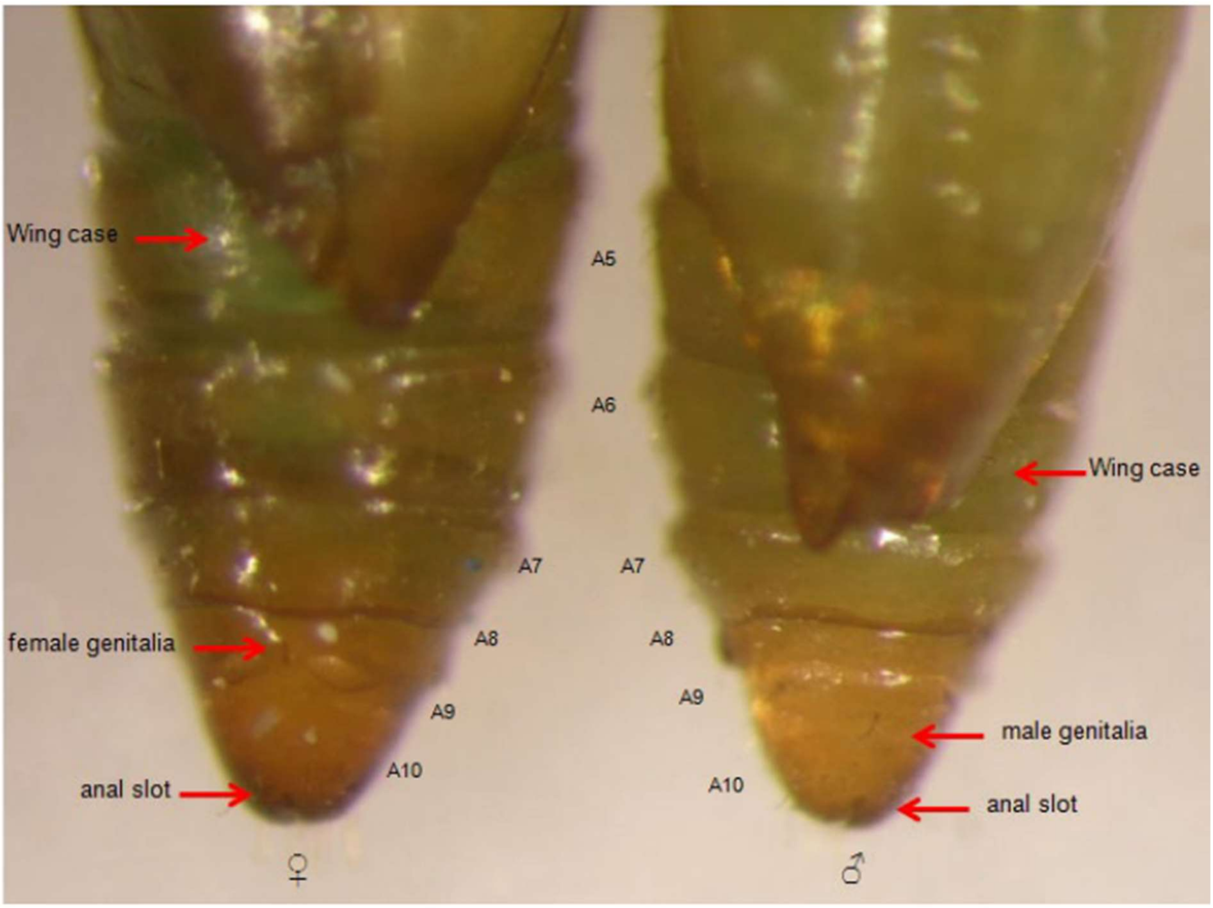


Figure 12: Ventral views of female and male pupae of the tomato leafminer.
Abdominal segments indicated as 5th (A5), 6th (A6), 7th (A7), 8th (A8), 9th (A9), and 10th (A10).
Source : Genç, 2016

Female pupae were isolated individually in 8.9 cm⌀ Petri dishes. After emergence, a moistened blotting paper was placed on the bottom of the Petri dish and a fresh tomato leaf was introduced to induce oviposition. The tomato leaves were removed daily and eggs were counted using a stereoscopic magnifier. New leaves were then placed back into the boxes to collect new eggs, doing so until the female died. The collected unfertilised eggs were incubated in Petri dishes and the emerged larvae (later called F2) were reared to pupal stage and sexed. A total of 25 female pupae (from unfertilised eggs) were then individually placed in new Petri dishes to test for vertical transmission of parthenogenesis. After emergence, tomato leaves free were provided for oviposition. Meanwhile, 20 pairs of pupae (1 male and 1 female) from each of the two populations were used as control to evaluate the average oviposition capacity of a mated female. Eggs were counted daily to compare the preferred oviposition period between virgin and mated females. We also measured the life expectancy of each female, the sex ratio and survivability of their offspring.

All data collected were first tested for normality. Data that followed a normal were subjected to an analysis of variance (95% confidence level). The non-parametric Kruskal-Wallis test was applied on data that did not follow a normal distribution. The life expectancy of mated and unmated females was analysed by Kaplan Meier and the two curves were compared using the log-rank method.

3 Results

3.1 Fertility

Since we found no difference of any kind between the two insect populations, we have decided to merge both data sets. The average number of eggs laid by a mated F1 female (57.4 ± 34.5 eggs) was much higher than by a virgin one (10.1 ±11.1 eggs) ($K= 29.54$, $P<0.001$). The same result applies on the F2 generation (43.6±16.0 eggs/mated female and 5.3±4.6 eggs/virgin female).

We found that fertilized females laid their eggs earlier in their life than virgin ones (figure 13). The peak of egg laying was observed on the third (28.1±19.4 eggs/female) and the first (30.0±10.8 eggs/female) day after emergence (DAE) in F1 and F2 fertilized females, respectively (figure 14). Virgin females also had two peaks of egg-laying, occurring on the 7th (3.8± 2.6 eggs/female) and on the 12th DAE (7.5 ± 7.8 eggs/female), for F1 and F2 respectively. Fertilized females (F1 and F2) laid most of their eggs (83.6% and 83.5%, respectively) during their first 5 DAE. Unmated females (F1 and F2) laid most of their eggs during the period of 6-10 DAE (55.6 and 53.6%, respectively). Few eggs were also laid in the interval 0-5 DAE (20.8% and 17.4%, respectively) as well as after 11 DAE (23.6 and 29%, respectively).

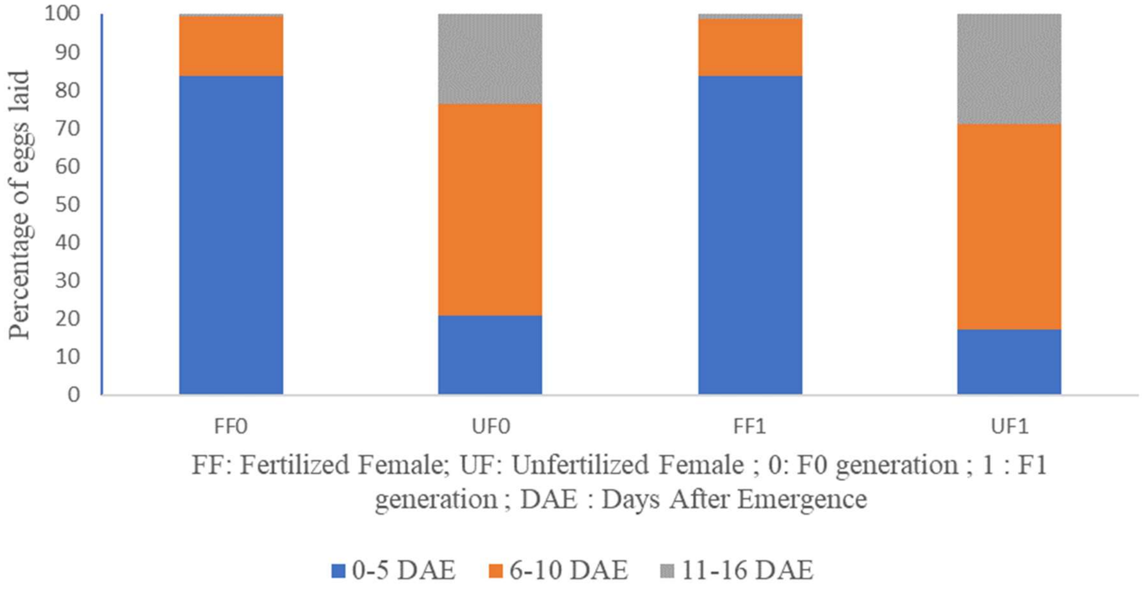


Figure 13: Egg-laying period of fertilized and unfertilized females

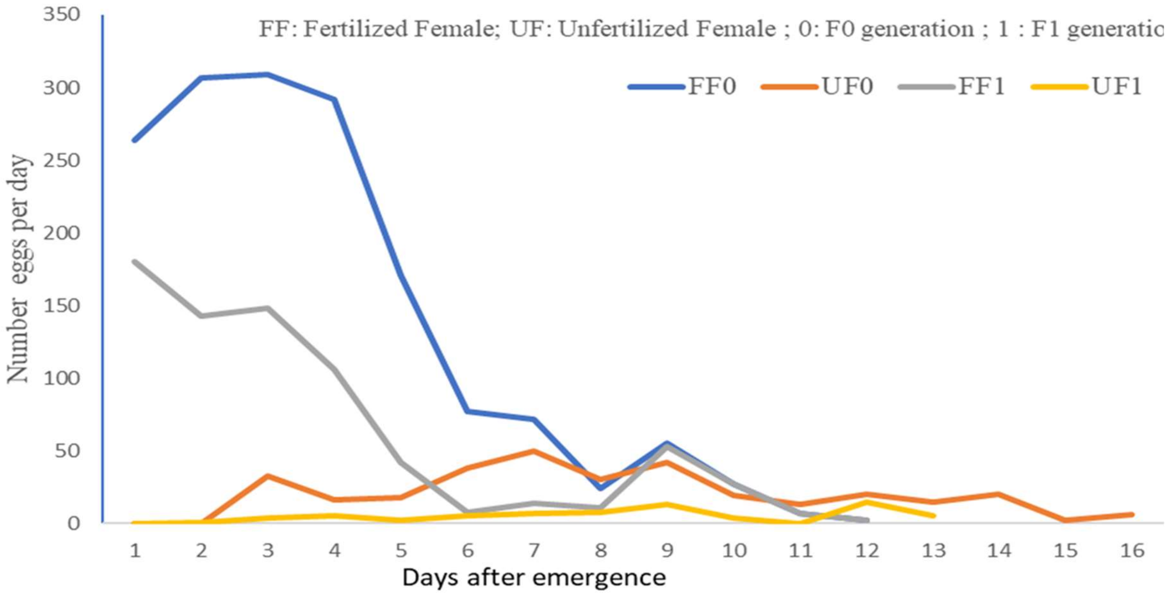


Figure 14: Daily laying per fertilized female and per unfertilized female

3.2 Life expectancy

Unmated females (9.8 ± 3.6 days) have a longer life expectancy than mated females (6.8 ± 3.1 days) (F =11.7, P=0.001) (Figure 15).

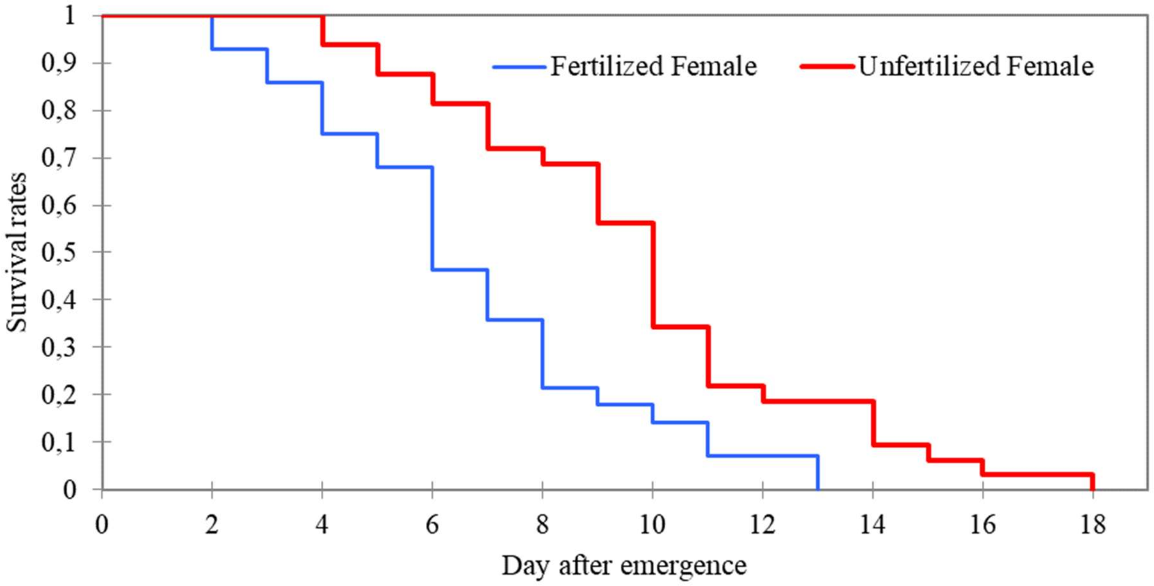
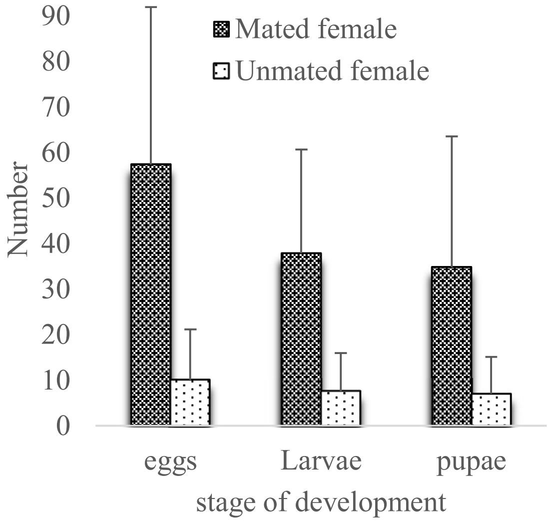


Figure 15 : Life expectancy of mated and unmated females

3.3 Life history traits

Comparable hatching rates were observed from virgin and fertilized eggs: 75.5% and 66.0%, respectively. As regard to the proportions of larvae becoming pupae, they were also found to be similar: 92.6% and 91.9% of the larvae originating from virgin and fertilized females, respectively. As a result of the initial fertility difference, we found that fertilized females (34.8±28.7 pupae/female) produce more pupae than virgin ones (7.0±8.1 pupae/female) (K=19.81, p=0.001) (figure 16). The sexing of the pupae shows that mated and virgin females produce as many males as females. Thus, each mated female produces 18.9±14.6 males and 19.4±14.2 females (K= 0.04, p=0.83); unmated female produces 4.2±3.7 males and 4.8± 4.8 (K= 0.23, p=0.63) (figure 17).



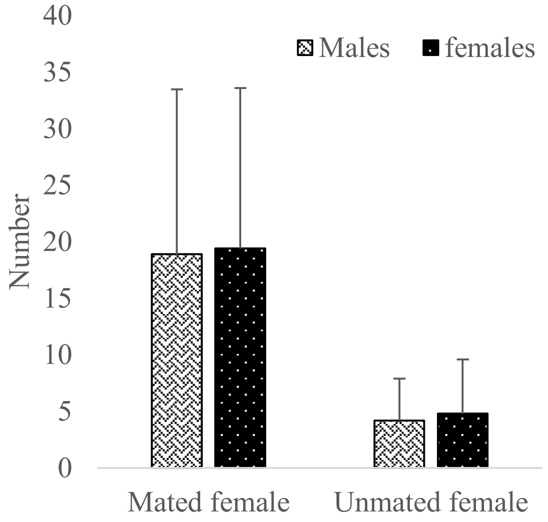


Figure 16 : Follow-up of the progenies produced by each fertilized and unfertilized

Figure 17 : Sex ratio of the offspring of fertilized and unfertilized females

3.4 Vertical transmission of parthenogenesis

Out of 50 female pupae from unmated females we obtained 70% emergence. Of these moths maintained individually without a male, 13 (37.2%) laid eggs (5.3±4.6 eggs/female). There was no difference between the number of eggs laid by F1 parthenogenetic females and their unmated offspring (k=3.14 p=0.08).

4 Discussion

Our results suggest strong differences in terms of fertility and oviposition periods in mated and virgin females. Regarding the necessary pre-oviposition period, our data confirm that mated individuals lay most of their egg load in the early five days of their adult life (Razuri & Vargas, 1975). However, unlike this study which mentions a pre-oviposition period of two days, we observed oviposition as early as the first day after emergence (Lee et al., 2014). The longer pre-oviposition period observed in virgin females suggest an adaptive strategy of retention of reproductive resources in the hope of encountering a mating partner. After this period (five days according to our data), the female maximises its fitness by laying unfertilised eggs (Menken & Wiebosch-Steeman, 1988; Suomalainen et al., 1976). Nevertheless, the laying of even a small number of parthenogenetic eggs in the first few days of its life suggests an intrinsic strategy to improve the survival of the species.

Mated females produce considerably more eggs than unmated females and, as a consequence, have shorter lives (Abbes & Chermiti, 2014). This difference in longevity can be explained by the fact that in moths, unmated females use the energy reserves normally allocated to reproduction (oocyte resorption) for somatic maintenance (Caballero-Mendieta & Cordero, 2013; Mori & Evenden, 2013). Our results are in agreement with those obtained by Lee et al. (2014b) who also found that the more often *T. absoluta* females mate, the larger their offspring. This is related to the amount of sperm females receive which is proportional to the number of matings (Lee et al., 2014; Seth et al., 2002).

We observed a deuterotokous parthenogenesis (each female, mated or not, produces about 50% males and 50% females). Similar results have been found with Tunisian, French and UK populations of *T. absoluta* (Abbes & Chermiti, 2014; Caparros Megido et al., 2012; Grant et al., 2021). Our data also suggests that *T. absoluta* populations in West Africa originate from these parental populations. Also, we expect that, over the course of their migration, they were not infested with symbiotic microorganisms, such as *Wolbachia* strains (ST41 and ST354), which are known to suppress this ability to reproduce by parthenogenesis (Carvalho et al., 2018; Nault et al., 2006).

The use of male annihilation techniques, using female sex pheromones, as a control strategy could be considered. Virgin females have indeed a lower fertility than mated ones, and start laying eggs later. The tomato production would therefore benefit from killing existing males. Because the number of eggs laid is proportional to the number of matings (Grissa-Lebdi et al., 2011; Lee et al., 2014) and because males are polygynous (Lee et al., 2014), pheromone-based strategies must be properly implemented to eliminate a high proportion of the male population. Also, strategies allowing infestation of a local leafminer population with *Wolbachia* bacteria could be of considerable benefit to the control of *T. absoluta*, especially if a semiochemical strategy of control is considered.

Partie IV : Lutte chimique contre *Tuta absoluta*

Avec l'arrivée de la mineuse au Burkina Faso, et son expansion fulgurante et très dommageable, les producteurs se sont rapidement tournés vers l’utilisation de produits phytosanitaires disponibles sur le marché local. L'inefficacité de plusieurs molécules a rapidement été rapportée de manière informelle auprès des conseillers agricoles. Il nous a semblé opportun d’identifier rapidement des molécules efficaces pour permettre au secteur de ne pas s'effondrer.

Nous avons parcouru la littérature afin d'identifier les molécules pour lesquelles des populations de mineuses ont déjà développé une résistance quelque part dans le monde. Nous avons également documenté les mécanismes déployés par le ravageur pour cette résistance.

La lutte chimique peut concerner en premier lieu les molécules naturelles, à courte rémanence et moins toxiques pour l'homme et l'environnement. Dans ce sens, nous avons d'abord passé au crible les biopesticides disponibles sur les places de marché du pays.

Comme de nombreuses populations de *T. absoluta* sont résistantes à plusieurs molécules, nous avons jugé bon de cribler toutes les molécules homologuées pour être utilisées dans la production maraîchère contre la mineuse des feuilles. De cette façon, nous avons pu obtenir une liste positive de molécules qui donneraient de bons résultats contre la mineuse si elles étaient utilisées selon les règles de l'art.

Chapter IV.1

Insecticide resistance in the South American tomato pinworm *Tuta absoluta*: A review

Chapter IV.1: Insecticide resistance in the South American tomato pinworm *Tuta absoluta*: A review

Wendnéyidé Mathieu SAWADOGO, Irénée SOMDA & François VERHEGGEN (in preparation). Insecticide resistance in the South American tomato pinworm *Tuta absoluta*: A review

Abstract

Introduction: *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a leafminer species originating in South America, whose primary host plant is tomato (*Solanum lycopersicum*L.). In the last three decades, the pest has spread and established itself in various countries of Europe, Asia, and Africa, where it is considered a pest of great economic importance, damaging both greenhouse and open-field tomatoes. *T. absoluta* is a challenging pest to control due to its rapid capacity to develop resistant populations against synthetic insecticides: Its short life cycle and high reproductive capacity drive its ability to develop resistance.

Literature: Thirty-eight published peer-reviewed studies have evaluated the efficacy (in field or laboratory) of at least one active substance against *T. absoluta*. A majority of the assays were conducted with South American populations, but most studies showed that *T. absoluta* can develop a wide range of resistance to a variety of chemical insecticide families, including Carbamates, Organophosphates, Pyrethroids, Avermectins, Azadirachtins, *Bacillus thuringiensis*, Benzoylureas, Diamides, Neonicotinoids, Nereistoxin analogues, Oxadiazines, Pyrroles, Spinosyns, Pyridalyl and Semicarbazones. Herein, we provide the mechanisms for insecticide resistance identified thus far for *T. absoluta*.

Conclusion: *T. absoluta* has shown its ability to develop resistance to 15 groups of active ingredients among which 30 molecules have been found ineffective. To avoid the rapid development of resistance, integrated pest management (IPM) approaches are necessary.

Keywords: tomato borer, invasive insect pests, active substance, integrated pest management

Résumé

Introduction : *Tuta absoluta* Meyrick (Lepidoptera : Gelechiidae) est une espèce de mineuse originaire d'Amérique du Sud, dont la principale plante-hôte est la tomate (*Solanum lycopersicum* L.). Au cours de ces trois dernières décennies, il s'est disséminé et s'est établi dans divers pays d'Europe, d'Asie et d'Afrique, où il est considéré comme un ravageur de grande importance économique, endommageant les tomates produites dans les serres et en plein champ. *T. absoluta* est un nuisible difficile à combattre du fait de sa capacité à développer rapidement des populations résistantes aux insecticides de synthèse : son cycle de vie court et sa capacité de reproduction élevée lui permettent de développer cette résistance.

Littérature : Trente-huit études publiées et évaluées par des pairs ont testé l'efficacité (sur le terrain ou en laboratoire) d'au moins une matière active contre *T. absoluta*. La majorité des essais ont été réalisés sur des populations Sud-Américaines, mais la plupart des études ont montré que *T. absoluta* peut développer une large gamme de résistance à une variété de familles d'insecticides, y compris les Carbamates, les Organophosphates, les Pyréthrinoïdes, les Avermectines, les Azadirachtines, *Bacillus thuringiensis*, Benzoylureas, Diamides, Neonicotinoids, Nereistoxin analogues, Oxadiazines, Pyrroles, Spinosyns, Pyridalyl et Semicarbazones. Nous présentons ici les mécanismes de résistance aux insecticides identifiés jusqu'à présent pour *T. absoluta*.

Conclusions : *T. absoluta* a démontré sa capacité à développer une résistance à 15 familles de substances actives dont 30 molécules se sont révélées inefficaces. Pour éviter le développement rapide de résistance, il est nécessaire d'adopter des approches de lutte intégrée (IPM).

Mots-clés : Pyrale de la tomate, insectes ravageurs envahissants, matière active, lutte intégrée contre les ravageurs.

1 Introduction

The South American tomato pinworm (*Tuta absoluta* Meyrick) (Lepidoptera: Gelechiidae) is a leafminer species considered to be one of the most devastating pests of tomato (*Solanum lycopersicum* L.) (Biondi et al., 2018). The spread of *T. absoluta* from South America to other areas of the world began in late 2006 after its detection in Eastern Spain (Urbaneja et al., 2007), probably by being transported on tomato plants and fruits. The species is now considered to be a priority target pest of tomato crops in Africa, Europe, and Asia (Biondi et al., 2018). Like other Gelechiidae pests of solanaceous crops, all *T. absoluta* larval stages feed on the mesophyll of the aerial parts of plants, including the stems, apices, leaves, flowers and fruits (Miranda et al., 1998). At high densities, the pest causes dramatic yield losses due to its leaf-mining activities and infestation of fruits (Desneux et al., 2010).

Until the 1980s, cartap hydrochloride (Nereistoxin analogues), permethrin (Pyrethroids), triazophos, methamidophos (Organophosphate), methomyl (Carbamates) and abamectin (Avermectins) were commonly used to control *T. absoluta* populations in South America (Souza & Reis, 1986). Later, chitin synthesis inhibitors (Diamides and Spinosyns) were added to the insecticide mix (Biondi et al., 2018). Although the primary method of control is repeated applications of various insecticide active substances, the chemical control of *T. absoluta* is controversial and typically results in disappointing results such as the development of insect's resistance to pesticides and the exhibition of detrimental side effects on non-target beneficial arthropods, which destabilize biodiversity dynamics and ecosystem services.

A number of difficulties are encountered when trying to control *T. absoluta* populations, including the endophyte mining behavior of the larvae, the fact that *T. absoluta* populations can quickly establish in tomato fields before plants reach their reproductive stage, and most importantly, the progressive reduction in the efficacy of some of the active substances in insecticides (starting in the early 1990s) (Siqueira et al., 2001). Resistance is defined by the Insecticide Resistance Action Committee (IRAC, 2018) as a "heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species." It is now clear that three decades of excessive chemical applications have led to the development of resistance in *T. absoluta* populations throughout the world (Biondi et al., 2018). The purpose of this paper is to provide a comprehensive overview of *T. absoluta* resistance to the insecticidal formulations used in its management.

To locate scientific literature concerning insecticide resistance in *Tuta absoluta*, we used the online search engines Scopus (Elsevier), PubMed, Google Scholar, Ms Academic, Scribe, and UniCat to query databases for all publications that used the scientific and common names potentially used for *Tuta absoluta.* We also included the terms “resistance,” “tolerance,” “pesticide,” and “insecticide”. Therefore, the terms were queried, as follows: ("*Tuta absoluta*" OR "*Phthorimaea absoluta*" OR "*Gnorimoschema absoluta*" OR "*Scrobipalpula absoluta*" OR "*Scrobipalpuloides absoluta*" OR "tomato leafminer" OR "tomato borer" OR "tomato pinworm" OR "tomato leaf miner" OR "South American tomato pinworm") AND (resistance OR tolerance) AND (pesticide* OR insecticide*). (The asterisk was used to include all words with the preceding word as its common core).

The first step of this literature search was completed between May and June 2018. In the second step, we completed another query by including the names of all insecticide families and active substances used to control Lepidopterans (however, we did not select any additional references following this search). We only selected published papers identified by the search whose abstracts described laboratory or field evaluations for the effects of insecticide application on the mortality and/or fecundity of *T. absoluta*. No papers published in non-peer-reviewed journals were considered, nor were review articles.

The following data were recorded from an in-depth reading of the selected papers: the country where the study was conducted, the year the study was conducted, the method by which resistance was evaluated, the insecticide(s) evaluated, the mode and site of action of the insecticide(s), the susceptibility of the insect to the insecticide (resistance ratio: RR_{50} which is the ratio between the lethal concentrations (LC_{50}) of the resistant populations by the lethal concentration (LC_{50}) of the sensitive population), and the mechanisms of resistance.

2 Litterature

2.1 The diversity of leafminer populations

We identified thirty-eight published, peer-reviewed journal articles focusing on field and laboratory studies that evaluated the efficacy of at least one active substance against *T. absoluta* (Figure 18). The tested *T. absoluta* populations occurred in fifteen countries across four continents: South America (Argentina, Brazil, Chile, and Bolivia), Europe (Spain, Greece, Italy, Portugal, Cyprus and United Kingdom), Western Asia (Iran, Israel, Kuwait and Turkey) and Africa (Nigeria). Five articles presented resistance assays performed in Europe, but used

T. absoluta populations obtained from other countries. Thirty-eight papers from fifteen countries examined resistance of *T. absoluta* populations to pesticides: Brazil (18), Italy (7), Greece (6), Spain (5), Turkey (4), Portugal (3), Iran (3), Chile (2), England (2), Argentina (1), Bolivia (1), Israel (1), Cyprus (1), Kuwait (1) and Nigeria (1) (Table 1). For each country, we recorded the relative resistance of *T. absoluta* to pesticides as either low, moderate, or high (Figure 19). The oldest article was published in 1983 in Bolivia (Moore, 1983). The first articles studying the resistance in European populations of *T. absoluta* were published in 2012 (Figure 18). Prior to 2012, published papers only dealt with South American populations. The number of published papers on this subject has recently increased, probably as a consequence of (i) the invasion history of this species, (ii) the development of resistant populations in the newly invaded areas, (iii) increasing prevalence of the damages, (iv) resulting to more scientists performing research on this important pest species.

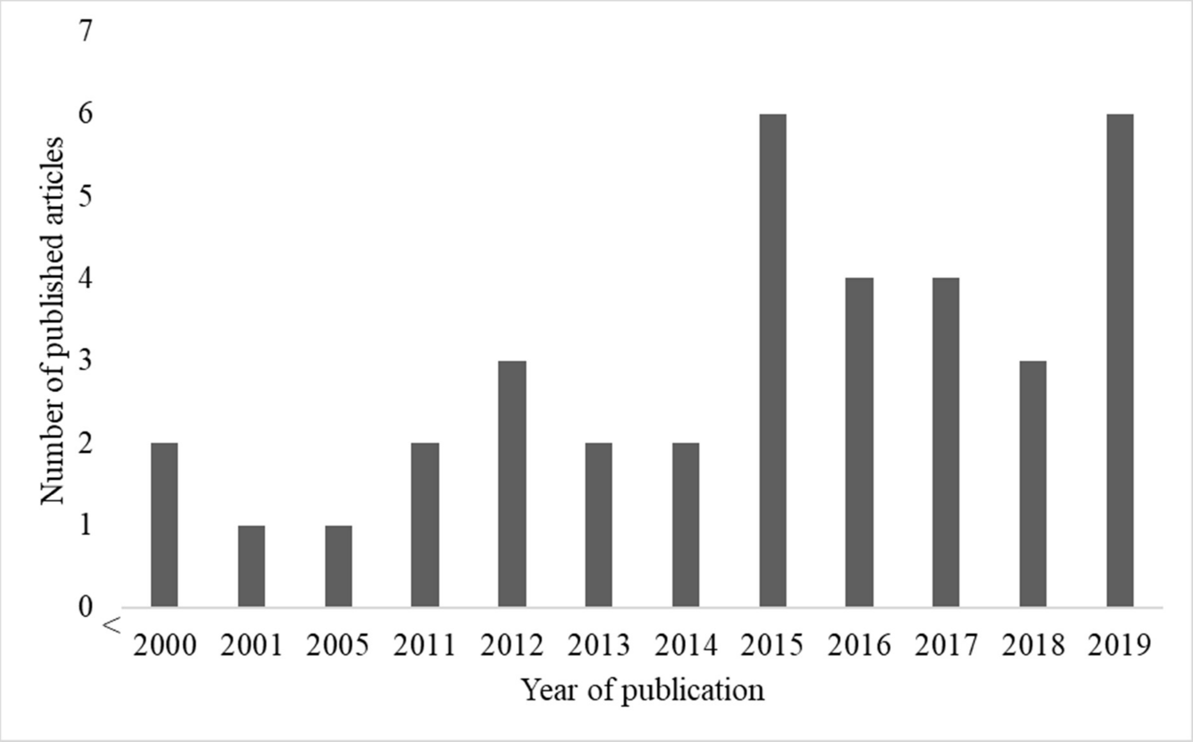


Figure 18: Evolution of the number of publications dealing with the resistance of *T. absoluta* to pesticides

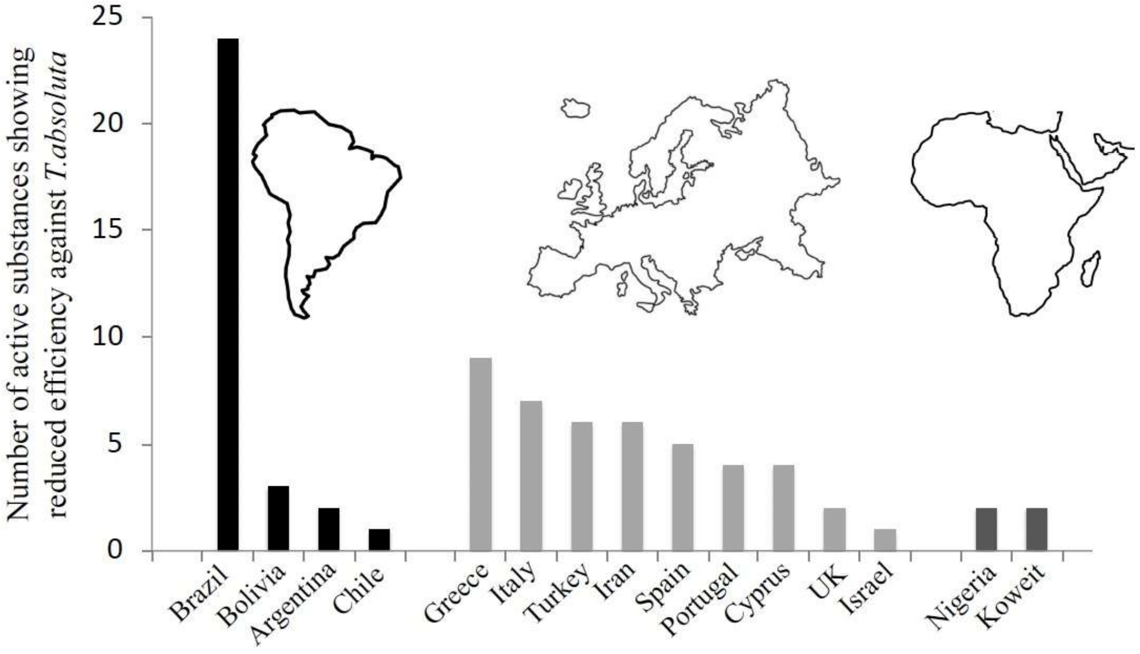


Figure 19: Number of active substances with reduced efficacy depending on the origin of the *Tuta absoluta* population

2.2 The diversity of methods used

Several methods were used to conduct the resistance studies we examined. The IRAC 022 method (**http://www.irac-online.org**) was applied in twenty-one studies, mainly evaluating the resistance of *T. absoluta* populations from Europe, Middle East and Africa. Because the description of this method is freely available online and it has been validated by international experts, this was the only method used in more recent articles (Barati et al., 2018a; Grant et al., 2019; Michaelides et al., 2019; Roditakis et al., 2018; Zibaee et al., 2018). In the IRAC 022 method, resistance monitoring is achieved by placing L2 larvae of the F1 generation (F0=field-collected larvae) on a tomato leaflet previously dipped in a test solution containing one dose of a single insecticide. A wide range of doses is typically tested. The evaluations are performed 72 hours after placing the larvae in contact with the treated leaflet. The investigator records whether or not the larva is able to make coordinated movements when delivered a gentle contact stimulus. The percent of damaged leaf area is also typically recorded to provide additional information on the reduction in feeding activity induced by the insecticide.

Other insecticide-resistance methods were used in the earliest studies. For most of these initial studies, resistance was tested in second instars and the number of replicates was sometimes low. Furthermore, rather than using tomato leaves as test substrate, some authors used an insecticide-impregnated filter paper onto which the larvae were placed (Siqueira et al., 2000a, 2000b; Siqueira et al., 2001). Mortality was sometimes assessed after a short period (48 hours) of exposure to the insecticide, justified by the fact that they were evaluating the efficiency of fast-acting neurotoxins (Campos et al., 2014, 2015a; Gontijo et al., 2012; Silva et al., 2011, 2015; Visintin et al., 2011). Conversely, when the researchers evaluated slow-acting insecticides, they evaluated larvae seven days after the larvae had been placed on tomato leaves impregnated with insecticide (Silva et al., 2011; Visintin et al., 2011). One study applied pesticides to the abdomen of the larvae using a micro-syringe equipped with a dispenser (Lietti et al., 2005).

2.3 The diversity of active substances

The first cases of insecticide-resistance in *T. absoluta* were observed in South America, where the insect first became a pest. The first reports occurred in the 1980s in Bolivia where *T. absoluta* developed resistance against organophosphates, carbamates, and *Bacillus thuringiensis*. In response, those preferred insecticides were replaced with pyrethroids (Moore, 1983). However, in less than a decade, *T. absoluta* developed resistance to the pyrethroids in areas where the insecticides were widely used, such as in Chile (LD_{50} has doubled in Ovalle and Quillota, two locations where *T. absoluta* shows the highest resistance) and Argentina (RR_{50}> 68.38-fold) (Lietti et al., 2005; Salazar & Araya, 2001). Avermectin (e.g., abamectin) and Nereistoxin analogues (e.g., cartap hydrochloride) were then tried, but resistant populations (9.37-fold and 21.9-fold respectively) emerged in Brazil in the 2000s (Siqueira et al., 2000b, 2000a; Siqueira et al., 2001). Benzoylureas (diflubenzuron, teflubenzuron, and triflumuron), Spinosyns (Spinosad) and Oxadiazine (indoxacarb) were then used to counteract resistance problems, but resistance to these insecticides was identified in populations of *T. absoluta* by the early 2010s (2.9 –222.7-fold for benzoylureas and 3.8 -27.3-fold for Oxadiazine) (Reyes et al., 2012; Silva et al., 2011; Visintin et al., 2011). In 2013, pyrroles (e.g., chlorfenapyr) were still effective (efficacy between 95% and 100%) against *T. absoluta* populations in Brazil (Gontijo et al., 2012). In 2015, some Brazilian populations also developed resistance to Diamides (44.5- 289.0-fold) and Spinosyns (up to 48,9-fold for selected spinosad-resistant strain) (Campos et al., 2015b, 2015a, 2014; Silva et al., 2016a; Silva et al., 2019). By 2016, *T.*

absoluta in Brazil had exhibited low resistance (4.6-fold) to halogenated pyrroles (chlorfenapyr) (Silva et al., 2016b).

In 2012, the first study of *T. absoluta* resistance to pesticides in Europe showed that all populations of *T. absoluta* collected from the field during the year 2010 in Spain, Italy and Portugal were resistant to the pyrethroids λ-cyhalothrin and *tau*-Fluvalinate, despite the fact that the pest had only arrived respectively in these countries in 2006, 2009, 2009 (Eppo, 2007; Urbaneja et al., 2007). Those studies indicate that *T. absoluta* was already probably resistant to pyrethroids before it was introduced to Europe (Haddi et al., 2012). By 2013, *T. absoluta* populations in Greece were also partially tolerant to Semicarbazones (metaflumizone) (17-40-fold), Diamides (chlorantraniliprole and flubendiamide) (4-fold) and Avermectins (emamectin benzoate) (3-16-fold) (Roditakis et al., 2013a). Later cases of tolerance to Oxadiazines (indoxacarb) (13-fold) and Spinosyns (spinosad) (33-fold or greater than 450) were reported respectively in Greece and England (Grant et al., 2019; Roditakis et al., 2018, 2017a).

The resistance of *T. absoluta* to Diamides (17-2704-fold) and Avermectins (emamectin benzoate) (4-35-fold) were recently observed in Italy (Roditakis et al., 2018). Recent reports from Europe confirm high resistance (8–9329-fold) to Diamides (chlorantraniliprole, flubendiamide, and cyantraniliprole) and Oxadiazines (indoxacarb) (Douris et al., 2017; Grant et al., 2019; Michaelides et al., 2019; Roditakis et al., 2017a, 2017b).

Although *T. absoluta* was first observed in Turkey in 2009 (Kiliç, 2010), by 2015 low to moderate resistance had occurred against Oxadiazines (indoxacab) (8-fold), Spinosyns (spinosad) (6.4-fold), Azadirachtin (1.2-fold), Diamides (chlorantraniliprole) (7.2-fold), and Semicarbazones (metaflumizone) (3.1- 4.0-fold) (Ugurlu Karaağaç, 2015; Yalçin et al., 2015). Karaagac, (2012) compared Pyridalyl LC50 of two populations: Ankara-Beypazari and Antalya-Serik, showing with the first one having a LC50 5.19-fold higher than that of the second population.

Low resistance to Organophosphates (11.5- 16.4-fold), Pyrethroids (2.7-13-fold), Avermectins (1.3 – 3.3-fold), and *B. thuringensis* (1.4 – 1.6-fold) has been recently reported in IRAN (Barati et al., 2018a; Zibaee et al., 2018).

In Kuwait, a low rate of resistance to Diamides (flubendiamide and chlorantraniliprole) was observed (2.7 - 3.9 - fold) (Jallow et al., 2018b). In Nigeria, Bala et al., (2019) reported resistance of the leafminer to Pyrethroid (λ-cyhalothrin) with low mortality (18.5% at 56 h) and an LD50 of 7461.5 ppm and to Carbamates (propoxur) and Organophosphates (chlorpyrifos-methyl) with average mortality of 56% and LD50 of 1023.5 ppm and 106.4 ppm, respectively.

Cross-resistance is a phenomenon where in resistance acquired against one insecticide is also gained against other chemically similar insecticides, even when the pest species has not been exposed to the other insecticides. Many cases of cross-resistance have been confirmed in *T. absoluta*. Haddi et al., (2012) found that mutations (M918T, T929, and L1014F) confer cross-resistance to all Pyrethroids. Cross-resistance between spinosad and spinetoram has also been demonstrated in *T. absoluta* (Campos et al., 2015a; Silva et al., 2016c). Resistance to indoxacarb confers as light resistance to emamectin benzoate and metaflumizone (Roditakis et al., 2017a). Some cases of cross-resistance have also been observed against Diamides (chlorantraniliprole, cyantraniliprole, and flubendiamide) (Campos et al., 2015b; Silva et al., 2016a; Silva et al., 2019). An Italian population of *T. absoluta* was obtained after four sequential selection cycles with the insecticide chlorantraniliprole (anthranilic acid diamides) using foliar applied doses of 100 mg L^{-1} (first selection) and 300 mg L^{-1} (subsequent selections) developed resistance against (phthalic acid diamides) flubendiamid (2,7-fold) (Roditakis et al., 2017b).

In summary, *T. absoluta* has developed resistance against a wide array of MOA (mode of action) chemical families (Groups), such as Carbamates (1A), Organophosphates (Group 1B), Pyrethroids (Group 3A), Neonicotinoids (Group 4A), Spinosyns (Group 5), Avermectins and Milbemycins (Group 6), *Bacillus thuringensis* (Group 11A), Pyrroles (Group 13), Nereistoxin analogues (Group 14), Benzoylureas (Group 15), Oxadiazines (Group 22A), Semicarbazones (Group 22B), Diamides (Group 28), Azadirachtins and Pyridalyl (Table 1). Within these MOA families at least one population of this pest has been shown to be resistant to at least one of 31 active substances, including abamectin, alpha-cypermethrin, azadirachtin, *Bacillus thuringensis,* bifenthrin, cartap, chlofenapyr, chlorantraniliprole, chlorpyrifos, Chlorpyrifos-methyl, cyantraniliprole, cypermethrin, deltamethrin, diazinon, diflubenzuron, emamectin benzoate, flubendiamide, indoxacarb, *lambda*-cyhalothrin, metaflumizon, methamidophos, permethrin, propoxur, pyridalyl, spinetoram, spinosad, *tau*-Fluvalinate, teflubenzuron, thiamethoxam, triflumuron, and triazophos.

2.4 Diversity in mode of action and resistance

Most of the above-listed insecticides act on insect' nervous system and associated muscles. The list below provides details about how these classes of chemical active substances work.

(1) Organophosphate and Carbamate pesticides bind to the acetylcholinesterase (ACE) active site and inhibit the breakdown of acetylcholine at the synaptic cleft, thus irreversibly impacting the normal functioning of the nervous system. This inhibition leads to an accumulation of acetylcholine in the synapses, which leaves the acetylcholine receptors permanently open, resulting in the death of the insect (Fournier, 2005). Part of an insect's tolerance to diazinon is due to the detoxification activity of monooxygenase and esterase enzymes (Barati et al., 2018a; Zibaee et al., 2018). In addition, a mutation (A201S) in the *ace-1* gene confers additional resistance to Organophosphates (chlorpyrifos and diazinon) (Haddi et al., 2017; Moradi et al., 2019; Zibaee et al., 2018) and is a dominant hereditary trait.

(2) Pyrethroids prevent the closure of voltage-gated sodium channels in axonal membranes, resulting in continuous nerve stimulation leading to paralysis and death in insects (Soderlund & Bloomquist, 1989). The activity of esterases and P450-dependent cytochrome monooxygenases is believed to be one mechanism responsible for the resistance of *T. absoluta* to deltamethrin and cypermethrin (Bala et al., 2019; Silva et al., 2015; Zibaee et al., 2018). Three kdr/super-kdr mutations (M918T, T929I, and L1014F) confer resistance of *T. absoluta* to Pyrethroids. However, these three mutations have never been previously observed to occur at once (Haddi et al., 2012; Silva et al., 2015; Zibaee et al., 2018). The L1014F mutation would confer resistance by causing the sodium channel to become less prone to opening (a conformational effect) (Davies & Williamson, 2009). The M918T mutation would confer the greatest resistance to Type II Pyrethroids, such as lamda-cyhalothrin and deltamethrin (Khambay et al., 1994). The mutation of T929I, in combination with mutation L1014F, causes sodium channels to become highly insensitive to a range of Type I and Type II Pyrethroid insecticides (Vais et al., 2001).

(3) Spinosyns target binding sites on nicotinic acetylcholine receptors (nAChRs) in insect nervous systems, which disrupts acetylcholine neurotransmission, resulting in tremors, paralysis, and death (Thompson et al., 2000). Spinosad resistance in *T. absoluta* is associated with an abnormal regulation of Taα6 splicing, resulting in a new form of insecticide resistance mediated by exon skipping. Taα6 of resistant *T. absoluta* populations lack exon 3 or 4, which

has been shown to be essential for receptor sensitivity to spinosad (Berger et al., 2016; Grant et al., 2019). Silva et al., (2016c) found that *T. absoluta* resistance to Spinosyns was also related to the G275E mutation (a single nucleotide change in exon 9 of the α6 subunit in resistant strains), which results in the replacement of glycine residue (G) in position 275 with a glutamic acid (E). A very intense selective pressure has led to a population of *T. absoluta* with extremely high levels of spinosad resistance (48,9-fold) (Silva et al., 2016c). The resistance of this strain is autosomal, hereditarily recessive, monofactorial, and exhibits strong cross-resistance to spinetoram (spinosoid). However, this strain has no resistance to thiamethoxam (a neonicotinoid) nor to insecticides targeting nicotinic acetylcholine receptors (nAChR) (Campos et al., 2014; Silva et al., 2016c). Reyes et al., 2012 showed that spinosad resistance in Chilean populations of *T. absoluta* is associated with an increase in cytochrome P450 dependent monooxygenases. However, a study of *T. absoluta* strains conducted by Silva et al., (2016c) found that a very high resistance to Spinosad was associated with an absence of metabolic activity / detoxification of enzymes in spinosad resistance. The β-esterase activity of *T. absoluta* populations has been correlated with susceptibility to spinosyn (Campos et al., 2015a).

(4) Avermectins and Milbemycins (both products of fermentation by *Streptomyces* spp.) activate glutamate chloride channels in neurons and myocytes, which cause neuronal hyperpolarization (IRAC, 2018; Roditakis et al., 2018). Siqueira et al., (2001) used enzyme inhibitors to determine the involvement of enzymes in the resistance of Brazilian populations of *T. absoluta* to abamectin. They found that esterase played a major role in abamectin resistance, that cytochrome P450-dependent monooxygenases probably play a secondary role, and that gluthatione S-transferases (GSTs) played a minor role. In addition, GSTs may play a supportive role by reducing the oxidative stress that develops during the metabolism of abamectin in abamectin-resistant populations of *T. absoluta* (Konus, 2014). The coexistence of various resistance mechanisms in the same populations of *T. absoluta* suggests an oligo or polygenic basis for resistance to abamectin (Siqueira et al., 2001).

(5) Nereistoxin analogues block nicotinic acetylcholine receptor (nAChR) channels (IRAC, 2018). Siqueira et al., (2000b) found that in cartap-resistant *T. absoluta* populations in Brazil, piperonyl butoxide was the most effective synergist and almost completely suppressed resistance to this pesticide in all study populations. These results suggest a major involvement of cytochrome P450-dependent monooxygenases as a resistance mechanism. The Siqueira et

al., (2000b) research also shows that glutathione-S-transferases and esterases appear to play a secondary role in cartap resistance in Brazilian populations of *T. absoluta*.

(6) Oxadiazines (with indoxacarb as the only active substance) are sodium channel blockers (Jiang et al., 2015) that require metabolic activation by the target pest before exhibiting insecticidal properties (Roditakis et al., 2017a). Roditakis et al., (2017a) found that F1845Y and V1848I mutations on the sixth segment of Domain IV of the sodium channel were strongly associated with indoxacarb-resistant phenotype, but a partial involvement of detoxification enzymes could also be detected.

(7) Diamides are modulators of ryanodine receptors and interfere with the release of calcium, thus disrupting normal muscle functioning (Roditakis et al., 2015). Roditakis et al., (2017b) found that mutations in the transmembrane domain of the ryanodine receptor (RyR) conferred resistance to diamide insecticides. Two of the mutations were novel (G4903V and I4746T) and two corresponded to previously described mutations in *P. xylostella* (G4946E and I4790M) (Guo et al., 2014; Troczka et al., 2012). Very high levels of resistance to chlorantraniliprole (9329-fold) and flubendiamide (4969-fold) and moderate levels against cyantraniliprole (191-fold) were found in populations of *T. absoluta* from Greece with mutant frequencies of 79% for G4946V and 21% for I4790M (Douris et al., 2017). *Drosophila melanogaster* experiments genetically modified with mutated *T. absoluta* genes show that flies bearing the G4946V mutation had high resistance ratios to flubendiamide (91.3-fold) and chlorantraniliprole (194.7-fold). Naturally wild flies with the I4790M mutation were moderately resistant to flubendiamide (15.3-fold), but significantly less resistant to chlorantraniliprole (7.5-fold) and cyantraniliprole (2.3-fold) (Douris et al., 2017). P450-monooxygenase cytochromes may play a key role in the development of chlorantraniliprole resistance in *T. absoluta* populations in Turkey (Campos et al., 2015b; Ugurlu Karaağaç, 2015).

Growth and development inhibitors are also used against *T. absoluta*. They include Benzoylureas (e.g., diflubenzuron), which inhibits the production of chitin, an important constituent of an insect's exoskeleton. Esterases appeared to play a major role in the development of metaflumizone resistance in populations studied in Turkey (Ugurlu Karaağaç, 2015).

3 Conclusion

T. absoluta has shown its ability to develop resistance to 15 groups of active ingredients in which 30 molecules have been found ineffective against certain populations of this pest worldwide. To avoid the rapid development of resistance, chemical control should be part of an insecticide resistance management strategy that should be part of an integrated pest management (IPM) approach. To do this, it will necessarily be necessary to raise awareness among producers about the adoption of these management strategies and to issue labels for production.

Table 1: Active substances where *Tuta absoluta* has developed low, moderate or high resistance.

Main Group and Primary Site of Action	Chemical Sub-group or exemplifying Active Ingredient	Active Ingredients	Resistance mechanism	Origin of the population tested	References
(1) Acetylcholinesterase (AChE) inhibitors Nerve action	1A Carbamates	Propoxur	Not studied	Nigeria	Bala et al. 2019
	1B Organophosphates	Chlorpyrifos	Mutations (A201S, L338M, F339M V204A…) in the active site cavity and its inferior area, the Protein gorge region (ace1).	Iran ; Spain, Italy, Portugal, Brazil	Moradi et al. 2019 Zibaee et al. 2018 ; Haddi et al. 2017 ; Campos et al. 2014 ; Roditakis et al. 2013 ;
		Chlorpyrifos-methyl	Not studied	Nigeria	Bala et al. 2019
		Diazinon	Increased activity of mono-oxygenases and esterases and the A201S mutation in ace1	Iran	Barati et al. 2018 ; Zibaee et al. 2018
		Methamidophos	Not studied	Argentina; Brazil	Lietti et al. 2005; Siqueira et al. 2000a
(3) Sodium channel modulators Nerve action	3A Pyrethroids Pyrethrins	Lambda- Cyhalothrin	Involvement of P450 monoxygenases and three kdr/super-kdr-type mutations (M918T, T929I and L1014F)	Nigeria; Spain, Italy, Portugal, Brazil	Bala et al. 2019; Haddi et al. 2012;
		Cypermethrin	Involvement Esterase and P450 monoxygenases and three substitutions in the sodium channel gene L1014F, M918T, T929I	Iran; Greece	Zibaee et al. 2018 ; Roditakis et al. 2013
		Deltamethrin		Iran; Brazil; Argentina; Chile	Zibaee et al. 2018 ; Silva et al. 2015 ; Lietti et al. 2005 ; Salazar & Araya 2001
		Permethrin	The activity of glutathione S-transferase and cytochrome P450-mediated N-demethylation and three substitutions in the sodium channel gene L1014F, M918T, T929I	Iran; Brazil; Bolivia	Zibaee et al. 2018 ; Silva et al. 2015 ; Campos et al. 2014 ; Silva et al. 2011 ; Visintin et al. 2011 ; Siqueira et al. 2000a; Moore 1983
		alpha-Cypermethrin	Three substitutions in the sodium channel gene L1014F, M918T, T929I	Brazil	Silva et al. 2015
		tau-Fluvalinate		Spain, Italy, Portugal, Brazil	Haddi et al. 2012

		Bifenthrin	Not studied	Brazil	Gontijo et al. 2013 ; Silva et al. 2011;
		Fenvalerate,	Not studied	Bolivia	Moore 1983
(4) Nicotinic acetylcholine receptor (nAChR) competitive modulators Nerve action	4A Neonicotinoids	Thiamethoxam	Not studied	Brazil	Campos et al. 2014;
(5) Nicotinic acetylcholine receptor (nAChR) allosteric modulators Nerve action	Spinosyns	Spinosad	Taα6 transcripts of resistant *T. absoluta* populations lack exon 3 or 4. we also have the G275E mutation. β-esterase activity of *T. absoluta* populations has been correlated with susceptibility to spinosyn	UK; Cyprus; Iran; Greece; Spain, Italy, Portugal, Brazil; Turkey; Chile	Grant et al. 2019; Michaelides et al. 2019; Barati et al. 2018; Roditakis et al. 2013, 2017b, 2018 ; Berger et al. 2016 ; Silva et al. 2016b ; Campos et al. 2015a ; Yalçin et al. 2015 ; Gontijo et al. 2013 ; Reyes et al. 2012 ; Silva et al. 2011 ;
		Spinetoram		Brazil	Campos et al. 2015a ; Campos et al. 2014
(6) Glutamate-gated chloride channel (GluCl) allosteric modulators Nerve and muscle action	Avermectins, Milbemycins	Abamectin	a major involvement of esterase and cytochrome P450 monooxygenase enzymes; the activity of glutathione S-transferase may also have a supporting role such as reducing oxidative stress	Nigeria; Iran; Brazil; Turkey; Argentina	Bala et al. 2019; Barati et al. 2018; Silva et al. 2016a; Campos et al. 2014; Konuş 2014; Gontijo et al. 2013; Karaagac 2012; Silva et al. 2011; Lietti et al. 2005; Siqueira et al. 2001, 2000a
		Emamectin benzoate	Not studied	Cyprus; Greece, Italia	Michaelides et al. 2019; Roditakis et al. 2013, 2017, 2018
(11) Microbial disruptors of insect midgut membranes	11A *Bacillus thuringiensis* and the insecticidal proteins they produce	*Bacillus thuringiensis*	Not studied	Iran; Brazil	Barati et al. 2018; Silva et al. 2011;
13 * Uncouplers of oxidative phosphorylation via disruption of the proton gradient Energy metabolism	Pyrroles	Chlorfenapyr	Not studied	Brazil	Silva et al. 2016a; Campos et al. 2014; Gontijo et al. 2013
(14) Nicotinic acetylcholine receptor	Nereistoxin analogues	Cartap hydrochloride	a major involvement of cytochrome P450-dependent	Brazil	Silva et al. 2016a; Campos et al. 2014; Siqueira et al. 2000a, 2000b

(nAChR) channel blockers Nerve action			monooxygenases as a cartap resistance mechanism also glutathione S-transferases and esterases seem to play a secondary role		
(15) Inhibitors of chitin biosynthesis, type 0 Growth regulation	Benzoylureas	Triflumuron	Not studied	Brazil	Gontijo et al. 2013 ; Silva et al. 2011
		Teflubenzuron	Not studied	Brazil	Gontijo et al. 2013 ; Silva et al. 2011
		Diflubenzuron,	Not studied	Brazil	Silva et al. 2011; Visintin et al. 2011
(22) Voltage-dependent sodium channel blockers Nerve action	22A Oxadiazines	Indoxacarb	F1845Y and V1848I mutations on the sixth segment of Domain IV of the sodium channel were strongly associated with indoxacarb-resistant phenotype	Cyprus; Greece, Italy, Israel; Brazil; Turkey	Michaelides et al. 2019; Roditakis et al. 2013 ; 2017b, 2018 ; Silva et al. 2016a ; Yalçin et al. 2015 ; Campos et al. 2014 ; Gontijo et al. 2013 ; Silva et al. 2011
	22B Semicarbazones	Metaflumizone	esterases might play a primary role in the development of resistance	Greece; Brazil; Turkey	Roditakis et al. 2013, 2017b ; Silva et al. 2016a ; Karaağaç 2012, 2015 ; Yalçin et al. 2015
(28) Ryanodine receptor modulators Nerve and muscle action	Diamides	Chlorantraniliprole	mutations (G4903V, I4746T G4946E, I4790M) in the transmembrane domain of the ryanodine receptor (RyR) have conferred resistance to diamide insecticides.	UK; Brazil; Kuwait; Cyprus; Greece; Italy; Spain; Brazil; Turkey	Grant et al. 2019; Silva et al. 2019; Jallow et al. 2019; Michaelides et al. 2019; Roditakis et al. 2013, 2015, 2017a, 2017b, 2018; Douris et al. 2017 ; Silva et al. 2016c ; Karaagac 2012, 2015 ; Campos et al. 2015b ; Yalçin et al. 2015 ; Campos et al. 2014 ;
		Cyantraniliprole	P450-monooxygenase cytochromes can play a key role in the development of chlorantraniliprole resistance	Greece; Brazil	Douris et al. 2017 ; Silva et al. 2016c ; Campos et al. 2015b
		Flubendiamide		Kuwait; Greece; Italy; Brazil	Jallow et al. 2019; Douris et al. 2017; Roditakis et al. 2013, 2015, 2017a ; Silva et al. 2016c ; Campos et al. 2015b ;
UN * Compounds of unknown or uncertain MoA	Azadirachtin	Azadirachtin	Not studied	Turkey	Yalçin et al. 2015
	Pyridalyl	Pyridalyl,	Not studied	Turkey	Karaağaç 2012

Chapter IV.2

Susceptibility of the tomato leafminer (*Tuta absoluta*) to various plant-based biopesticides

Chapter IV.2: Susceptibility of the tomato leafminer (*Tuta absoluta*) to various plant-based biopesticides

This chapter is an adapted version of the article

Wendnéyidé Mathieu SAWADOGO, Besmer Régis AHISSOU, Irénée SOMDA, Souleymane NACRO, Anne LEGRÈVE & François VERHEGGEN (under revisions). Susceptibility of the tomato leafminer (*Tuta absoluta*) to various plant-based biopesticides. Scientific African.

Abstract

The tomato leafminer *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a worldwide invasive pest of tomatoes 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 in the West African market, for their ability to control *T. absoluta*. We followed the IRAC022 methodology, consisting in leaf/egg dip bioassay–, to compare both the ovicidal and the larvicidal activity of these biopesticides, at various concentrations of active ingredients.

We found, for each tested biopesticides, the larva lethal concentrations (LC) (8.2 - 41.1 $ml.l^{-1}$) to be lower than those necessary to stop egg hatching (26.7 - 409.7 $ml.l^{-1}$). Two products, both based on *Azadirachta indica* extracts and bark of *Khaya senegalensis*, 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 based on *Mitracarpus scaber* 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 a proper communication is made toward West African tomato producers to encourage them to use the most efficient biological products available.

Key words: Biopesticide, *Tuta absoluta*, *Azadirachta indica*, *Khaya senegalensis,* control failure likelihood

1 Introduction

The tomato leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is a worldwide invasive insect pest, that colonized Europe, Africa, Asia and the Caribbean during the last two decades (Biondi et al., 2018a; Son et al., 2017a; Verheggen & Fontus, 2019). It feeds mainly on the Solanaceae, with a preference for tomatoes, where 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 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; 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., 2019b; 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 & Biondi, 2021). Different biological products based on plant extracts have also 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 Euphhorbiaceae, 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.

2 Material and methods

2.1 Insect

Approximately 1200 larvae were collected between February and April 2020 in open tomato fields located in the proximity of Bobo Dioulasso (Burkina Faso) and brought to the laboratory. Insects were placed in rearing cages 80×40×40cm and fed tomato plants (v. 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 rearings and bioassays were carried out at temperatures of 28 ± 3° C, relative air humidity of 55 ± 15% and under a 12:12 photoperiod.

2.2 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 hours after adult oviposition, keeping them attached to their tomato leave. According to Ekesi et al., (2002), the leaves were soaked for 3 seconds in the test solution, in which a wetting agent (triton X100 at 0.2 $g.l^{-1}$) was previously added. Different concentrations of each biopesticide solution were tested and 35 eggs were used for each of them. After soaking, the tomato leaves (with eggs on them) were dried for 30 min under laboratory conditions. They were then placed in Petri dishes containing a slightly moistened blotting paper and sealed with Parafilm. Distilled water containing triton X100 (0.2 $g.l^{-1}$) was used as control. Observations with a binocular magnifying glass were conducted each morning and evening to monitor the evolution of egg hatching.

2.3 Larvicidal activity

The IRAC 022 methodology (www.irac-online.org) was followed to evaluate the larvicidal activity of the nine biopesticides. Tomato leaves were soaked for 3 seconds in a given concentration of one of the tested insecticides (triton X100 at 0.2 $g.l^{-1}$ was added) before being dried for 30 minutes. Each larva was then placed in a Petri dishe containing a slightly moistened blotting paper and one treated tomato leave. A total of 32 larvae were tested for each concentration of each biological insecticide. A control treatment (distilled water + triton) following the same procedure as above was set up to validate the bioassays. Larval mortality was assessed 72 h after soaking and any larvae failing to make a coordinated movement after three consecutive stimulations with a pair of forceps were considered dead.

2.4 Bioinsecticides

All plant-based insecticides available on local markets in Burkina Faso were purchased and included in the assays (Table 2).

Table 2: List of the nine biopesticides used in the assays, including their active ingredients and recommended doses by the manufacturer.

Manufacturer	Trade name	Active ingredient	Manufacturer recommended dose (ml.l^{-1})
Bioprotect	HN	Extracts of *Azadirachta indica*	11.5
	Piol	Extracts of *Capsicum annuum*, *Allium cepa*, *Allium sativum*, *Azadirachta indica*	13.6
	Limosain	Natural flavours, Mn, B, MaO, D-limonene Extracts of *Pinus* sp.,	6.8
	Biopoder	Extracts of *Azadirachta indica*, *Brassica* sp., *Capsicum annuum*, *Allium sativum*, and *Mentha* sp	12.6
	HNN^{+}	Extracts of *Azadirachta indica*	7.6
	HNN^{++}	Extracts of *Azadirachta indica*	7.6
Action Research Group Zems-Taaba of ADESVK	Bangr-pougo (BP)	Extracts of *Mitracarpus scaber* and *Khaya senegalensis*	200
	Bangr-kièta (BK)	Extracts of fruit and leaf of *Azadirachta indica* and extracts of bark of *Khaya senegalensis*	200
	Bangr-pougo (BP) formulated in powder	Extracts of fruit and leaf of *Azadirachta indica* and extracts bark of *Khaya senegalensis* (powder)	10 (g.l^{-1})

2.4 Statistical analysis

Mortality rates were corrected using the Abbott formula (Abbott, 1925), 1925). A probit dose-response analysis was performed on the corrected data to determine the lethal concentrations for each biopesticide tested. Based on the manufacturers' recommended doses, we used the formula of Guedes (2017) to calculate control failure likelihood (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 (table 3 and 4), the values (responses) predicted by the log (dose) / probit (mortality) model did not differ significantly from the values observed in the bioassays, so the probit model was found suitable for concentration ± response analyses.

3 Results

3.1 Ovicidal activity

The ovicidal effect of the nine biocidal products are presented in Table 3, including their LC50, LC80 and control failure likelihood. BK and BP powder are the only two products being able to significantly reduce larva emergence. Two products show low ovicidal activity: HN and BP, with CFL of 71% and 64%, respectively. The other five bioinsecticides are unable to control egg hatching, with control failure likelihood above 85%.

3.2 Larvicidal activity

The larval toxicity levels of the nine biopesticides are listed in Table 4. BP, BK and BP powder eliminated >80% of *T. absoluta* larvae, at the manufacturer's recommended doses. They are followed -in terms of efficacy- by HN, HNN^{++} and Biopoder (their LC50 confidence limits overlap) which had control failure likelihood of 30, 40% and 47.5%, respectively. The last three biopesticides (Limosain, Piol and HNN^{+}) have similar levels of toxicity (overlapping LC50 confidence limits) were the least effective against *T. absoluta* L2 larvae (55≤CFL≤76.2%).

Table 3: Ovicidal effects of nine biopesticides on *T. absoluta*

Bio insecticides	N	LC_{50} (ml.l^{-1})	Confidence Level (95%)	LC80 (ml.l^{-1})	Confidence Level (95%)	Slope±SE	χ2	Control Failure Likelihood
HN	105	26.7	20.5-46.8	43.3	31.8-88.2	0.05±0.02	0.34	71.2%
Piol	140	67.3	59.1-83.4	91.6	77.8-127.7	0.04±0.01	0.46	95.6%
Biopoder	175	106.2	88.9-173	163.7	129.9-482.8	0.02±0.01	0.11	89.4%
Limosain	210	409.7	344.5-518.2	587.6	488.6-794.4	0.01±0.00	0.23	96.9%
HNN^{+}	140	61.6	52.5-76.9	91.6	76.5-123.3	0.03±0.01	0.38	92.5%
HNN^{++}	175	49.8	40.0-60.3	79.1	66.7-110.9	0.03±0.01	0.45	86.2%
BP	210	303.6	253.5-418.6	449.2	359.9-690.3	0.01±0.00	0.03	63.7%
BK	175	61.3	47.7-71.0	92.9	81.6-116.7	0.03±0.01	0.1	<1%
BP powder	210	93.7	79.6-107.3	141.8	125.6-168.5	0.02±0.00	0.24	<1%

N = number of tested eggs; LC = Lethal concentration; SE = standard error of slope; χ2: Chi-square testing linearity of dose–mortality response; LC are expressed in mg.l^{-1} for BP powder.

Table 4: Larvicidal effects of biopesticides on L2 *T. absoluta* larvae

Bio insecticides	N	LC_{50} ($ml.l^{-1}$)	Confidence Level (95%)	LC80 ($ml.l^{-1}$)	Confidence Level (95%)	Slope±SE	χ2	Control Failure Likelihood (%)
HN	320	9.1	0.8-14.1	24.2	18.7-37.1	0.06±0.008	18.4	30
Piol	288	29.4	24.1-34.7	57.6	49.5-72.1	0.03±0.005	10.7	60
Biopoder	288	22.8	11.8-31.5	71.5	58.5-95.8	0.017±0.003	3.2	47.5
Limosain	384	25.7	13.4-35.5	69.2	54.2-107.4	0.19±0.003	15.5	55
HNN+	352	28.2	22.1-36.4	48.2	39.2-66.8	0.42±0.005	21.4	76.2
HNN++	352	8.9	4.5-12.7	31.9	26.1-42.2	0.037±0.006	13.3	40
BP	320	41.1	34.1-48.8	81.6	70.0-101.0	0.021±0.003	10.7	<1%
BK	320	36.0	32.0-40.3	58.1	52.3-66.3	0.038±0.004	11.9	<1%
BP powder	320	8.20	-3.5-15.2	38.0	32.4-45.8	0.028±0.005	4.9	<1%

N = number of tested larvae; LC = Lethal concentration; SE = standard error of slope; χ2: Chi-square testing linearity of dose–mortality response. LC are expressed in $mg.l^{-1}$ for BP powder.

4 Discussion

The biopesticides we used are formulated from several botanical species that have each shown insecticidal activity. For example, studies conducted by 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 clearly show the insecticidal effects of metabolites or secondary metabolites from species such as *C. annuum, A. sativum, A. cepa, M. arvensis, M. scaber, Pinus sp, Brassica sp* and *K. senegalensis*. D-Limonene, the main constituent of Citrus bark oil, is a monoterpene with good ovicidal and larvicidal activity (Chaieb et al., 2018). Combinations of several plant extracts is expected to have synergistic effects allowing for better efficacy and control of a wide range of insects. Azadirachtin, a triterpenoid acting through inhibition of feeding, oviposition (Arnó & Gabarra, 2011) and growth regulation (Schlüter et al., 1985) is one of the main biological molecules used today in leafminer control (Biondi et al., 2018; Guedes et al., 2019). It is reported to have a weak effect on leafminer beneficials, including adults of *Macrolophus pygmaeus*, *Trichogramma cacoeciae* and the nematode *Steinernema feltiae* (Amizadeh et al., 2019; Arnó & Gabarra, 2011; Cherif et al., 2018). It could have similar efficacy to indoxacarb, metaflumizone and abamectin (Nannini et al., 2011). However, it has been shown that some populations (Urla) of *T. absoluta* are not very sensitive to this molecule, which requires additional action to control the leafminer (Yalçin et al., 2015).

For all biological insecticides tested, the required LC50s -and their confidence levels- are much higher to control eggs than larvae. The egg shell protects the embryo from all external toxins. Consequently, a biocidal product usually requires higher doses to prevent egg hatching than to kill larvae (Campolo et al., 2017; Chegini et al., 2018). In addition to the botanical species included in the biopesticides we used; other studies have also shown ovicidal effects of plant-based insecticides. These were the essential oil of *E. cardamomum* and *Z. multiflora* which had LC50s of 351.2 and 60.3 µl of air L^{-1} respectively (Chegini et al., 2018).

Considering that only BK and BP powders had a good ovicidal effect (CFL= 0%), it would be beneficial to increase the recommended dose for the other biopesticides, if the intention is to use them to control the egg stage of *T. absoluta*. However, one should keep in mind that the tomato leafminer lay most of its eggs on the underside of the leaves (Cherif et al., 2013) and are therefore difficult to reach with any sprayable 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 (by consuming the treated plant parts).

Even if all tested biopesticides have a proven larvicidal effect, at the manufacturer recommended doses, only BK, BP and BP powder have acceptable control failure likelihood. Increasing the recommended doses would therefore allow a better efficacy of the other biopesticides against *T. absoluta*. Several other biopesticides in the form of essential oils have shown larvicidal effects on *T. absoluta*. For example, the essential oil of *T. capitatus* and *T. articulata* at 0.2 $ml.l^{-1}$ of air induced 80% mortality of all instars and 100% mortality of first instar larvae after 1.5 hour of exposure (Alam et al., 2017). Citrus peel essential oil in foliar application gave similar results after 72 hours with a concentration of 40 $g.l^{-1}$ (Campolo et al., 2017). Under greenhouse, Prev-am® essential oil (composed of orange oil, salt borax and biodegradable surfactants; ORO AGRI International Ltd), 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 24 mg L^{-1}) in combination with the generalist predator *Nesidiocoris tenuis* (Soares et al., 2019).

Chapter IV.3

Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso

Chapter IV.3: Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso

This chapter is an adapted version of the article

SAWADOGO M.W., SOMDA I., Nacro S., LEGRÈVE A.L. & VERHEGGEN F. J., 2020, Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso. Physiological Entomology, 1-7. https://doi.org/10.1111/phen.12332

Abstract.

The South American tomato pinworm, *Tuta absoluta* Meyrick (Lepi- doptera: Gelechiidae) is a leafminer species currently considered as one of the major pests of fresh tomatoes around the world. The species settled in north Africa in 2007, before being observed in the entire continent. Widespread insecticide use has led to the emergence of resistant populations in South America and Europe, but no large-scale insecticide resistance assessment has been performed in Sub-Saharan Africa so far. In this study, we collected *T. absoluta* larvae from locations widely distributed in Burkina Faso, where the pest was first detected in 2016. Acute toxicity of the all-available molecules in Burkina Faso was evaluated in the laboratory on F1 individuals, including acetamiprid, abamectin, spinosad, cypermethrin, chlorpyrifos, λ-cyhalothrin, deltamethrin, and *Bacillus thuringiensis*. No LC50 differences among *T. absoluta* populations were highlighted, except for *Bacillus thuringiensis*. Insects were still highly susceptible to abamectin [LC50 < 0.4 $mg.l^{-1}$; Control failure likelihood (CFL) =0%], spinosad (LC50 < 0.6 $mg.l^{-1}$; CFL = 0%) and chlorpyrifos-ethyl (LC50 between 254 and 458 $mg.l^{-1}$; CFL =0%), but were less susceptible to acetamiprid (CFL ranging from 72% to 91%), cypermethrin (CFL = 80%), λ-cyhalothrin (CFL =79%), and deltamethrin (CFL ranging from 51% to 66%), with LC50 values for these insecticides ranging between 100 and 525 $mg.l^{-1}$. Pending a proper communication strategy, we hope this work could help producers avoiding the most inefficient active substances.

Key words. abamectin, acetamiprid, acute toxicity, *Bacillus thuringiensis*, chlorpyri- fos, pyrethroids, spinosad.

1 Introduction

The South American tomato pinworm *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a leafminer species currently considered to be one of the major pests of tomato (L.) (Biondi et al., 2018). Like other Gelechiidae, all *T. absoluta* larval stages feed on the mesophyll of aerial parts of plants, including stems, apexes, flowers, fruits, and leaves (Abbas et al., 1993; Miranda et al., 1998; Pouey et al., 1994). At high density, the pest causes significant yield losses due to leaf and fruit damages (Desneux et al., 2010). From its area of origin, a Chilean population of this pest was introduced in Spain in 2006 (Biondi et al., 2018; Guillemaud et al., 2015; Urbaneja et al., 2007), then spread over the Mediterranean littoral (Desneux et al., 2011, 2010), including North Africa in 2007, and arrived in West Africa in 2012, probably first in Senegal (Mansour et al., 2018; Pfeiffer et al., 2013). In 2016, it was reported for the first time in Burkina Faso (Son et al., 2017a), a country where tomato cultivation plays a very important socio-economic role (MAH, 2011) with an estimated 12 635 tonnes in 2017 (FAOSTAT, 2019). Unfortunately, very few insecticide formulations are registered for the control of this new pest, leading tomato producers to use any available substances to attempt to reduce yield loss. During preliminary surveys performed by the authors, many of them have testified their inefficiency, with the result that many producers ended up abandoning their fields at the mercy of *T. absoluta*. The plausible explanation for these treatment failures is that the introduced pest has developed resistance mechanisms (Guedes & Siqueira, 2012). Indeed, several studies performed over the world show that certain *T. absoluta* populations are resistant to several molecules, including abamectin, alpha-cypermethrin, azadirachtin, bifenthrin, cartap, chlorantraniliprole, chlofenapyr, chlorpyrifos, cyantraniliprole, cypermethrin, deltamethrin, triazophos, diazi- non, diflubenzuron, emamectin benzoate, flubendiamide, indoxacarb, metaflumizon, methamidophos, permethrin, spine- toram, spinosad, tau-fluvalinate, teflubenzuron, thiamethoxam, triflumuron, pyridalyl, *Bacillus thuringensis*, and λ cyhalothrin. *T. absoluta* would mainly use two types of mechanisms to develop resistance to pesticides. The first one involves detoxifying enzymes, including esterases and monooxygenases, dependent on cytochrome P450 (Barati et al., 2018a; Campos et al., 2015a, 2015b; Reyes et al., 2012; Silva et al., 2015; Siqueira et al., 2001; Siqueira et al., 2000a; Ugurlu Karaağaç, 2015; Zibaee et al., 2018). The second mechanism involves mutations in the pest genome (Berger et al., 2016; Douris et al., 2017; Grant et al., 2019; Haddi et al., 2012, 2017; Moradi et al., 2019; Roditakis et al., 2017b, 2017a; Silva et al., 2015; Silva et al., 2016; Zibaee et al., 2018). These resistance mechanisms were previously shown to lead treatment failures in the field (Haddi et al., 2017, 2012; Roditakis et al., 2018, 2013a, 2013b; Silva et al., 2011, 2015), resulting in the farmers to overuse pesticides by increasing doses and frequencies of applications, and subsequently harm human, animal, and environmental health (Mirhosseini et al., 2019; Moradi et al., 2019). We, therefore, decided to conduct this study to evaluate the

sensitivity of four populations of *T. absoluta* collected in the open-field cultivations to the main molecules commercialized in Burkina Faso, in the hope we could recommend avoiding the use of particularly inefficient active substances.

2 Materials and methods

2.1 Insects

We collected *T. absoluta* individuals from four populations in Burkina Faso (Figure 20). Growers complained about the ineffectiveness of pesticides against this pest at all four locations. Insects were collected from cultivated tomato plants as larvae (200–300 individuals/population), and were brought to the laboratory at the Training and Research Center of the University Nazi Boni (UNB) in Bobo Dioulasso (Figure 20). The populations of Ouahigouya and Lombila were collected between October 16 and 18, 2018 and those of Goue and Pindga between January 10 and 13, 2019. The larvae were fed with pesticide-free tomato cv. Mongal leaves, in 80×40×40 cages with a relative humidity of 50±15% and with a controlled temperature of 28±3°C, and a photoperiod of

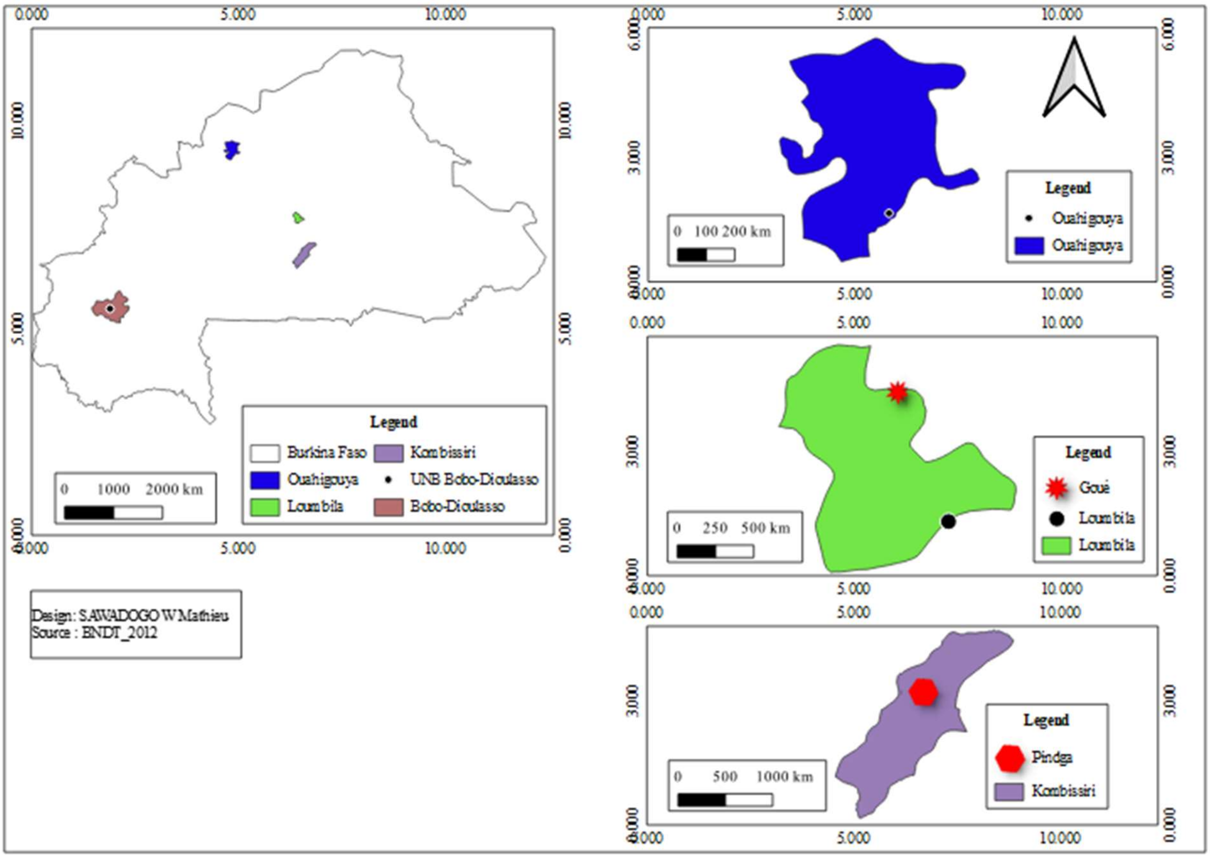


Figure 20: Location of the four collected *T. absoluta* populations

2.2 Insecticides

No insecticides are specifically registered for the control of *T. absoluta* in the 13 countries that make up the Sahelian Pesticides Committee (SPC) (see list of approved pesticides at http://insah.cilss.int/index.php/csp/). To achieve this experiment, we selected eight single active ingredient insecticides registered for tomato production and available on the market: the neonicotinoids acetamiprid 25 gL^{-1} (emulsifiable concentrate - EC) (Titan 25 EC, Arysta Lifescience, recommended dose RD= 1.5 L ha^{-1}), avermectins/milbemycins abamectin 18 gL^{-1} EC (Abalone 18 EC, Arysta Lifescience, RD = 1Lha^{-1}), spinosyns spinosad 0.24 gL^{-1} CB (Success appât 0.24 CB Dow Agrosciences Export S.A.S, RD = 1Lha^{-1}), organophosphate chlorpyrifos 480 gL^{-1} EC (Pyrical 480 EC, Arysta Lifescience, RD = lLha^{-1}), *Bacillus thuringiensis* var. Kurstaki 16 000 UI/mg (Bio K 16, Savana, RD = 1.5 kg ha^{-1}) and pyrethroids cypermethrin 50 gL^{-1} EC (Cypercal 50 EC, Arysta Life- science, RD = 1Lha^{-1}), λ-cyhalothrin 25 gL^{-1} EC (Lambda power, Zhejiang Chemical I/E Crop, RD = 0.8 L ha^{-1}), and deltamethrin 25 gL^{-1} EC (Tamega, Savana, RD = 0.5 L ha^{-1}).

2.3 Insecticide assays

The bioassay was conducted in accordance with the *T. absoluta*-specific IRAC method n∘22 (detailed on www.irac-online .org). In brief, L2 larvae of a population of *T. absoluta* were fed fresh young tomato leaves previously soaked for 3 s in a given concentration of a commercial product containing Triton X100 wetting agent (0.2 g.L^{-1}) and dried for 30min. A control treatment without insecticide (distilled water + Triton X100) is used to record natural mortalities. Leaflets were then placed in a Petri dish containing moisten filter paper and sealed with parafilm. Five or six larvae were introduced in each Petri dish, stored at a temperature of 28±3°C and a relative humidity of 50±15%, as described in Roditakis et al. (2013a, 2013b) and Michaelides et al. (2019). A total of 32 larvae per insecticide concentration were tested: three Petri dishes containing five larvae and two Petri dishes containing six larvae were used. A minimum of six different concentrations were tested per insecticide product. Mortality rates were assessed 72 h after the larvae were introduced in the Petri dishes. Larvae were considered dead if they were unable to make coordinated movement from gentle stimulus with a fine pointed forceps.

2.4 Statistical analyses

As suggested by the above- mentioned IRAC method, mortality percentages generated in dose–response bioassays were calculated using Abbott's formula (Abbott, 1925) to take into account mortality observed in untreated control. Using Stat- graphics 18 software, mortality percentages were then subjected to a Probit Analysis (commonly used in toxicology to determine the relative toxicity of chemicals to living organisms) following Finney (1964) to obtain lethal concentration (LC) estimates for each insect population tested. The control failure likelihood (CFL) was calculated according to the method described by Guedes (2017) : CFL = 100− [achieved mortality (%)× 100]/expected mortality (80% for SPC). The resistance ratio (RR) is the quotient of the LC50 value of different populations on the value of the population with the smallest LC50 value.

3 Results

Table 5 lists all results of the Probit Analysis. For all tested molecules, the theoretical values did not differ significantly from the observed values (low χ2values; P-values >0.05). The Probit model was, therefore, considered suitable for all following analyses. There was no significant difference between acetamiprid LC50 values for the 4 populations. LC50 are 485.6, 455.8, 363.5, and 340.5 mg.L^{-1} for the populations of Goué, Pindga, Ouahigouya, and Loumbila, respectively. Very high control failure likelihood ranging from 72% to 91% have been observed. The slopes of the concentration/mortality curves ranged from 0.003 to 0.006, showing similar responses for all populations. Low slope values mean that to increase slightly larval mortality, a large increase in insecticide concentration is required, suggesting a high level of resistance to this molecule. Abamectin LC50 values were similar for all four populations: 0.33, 0.26, 0.26, and 0.22 mg.L^{-1} for the populations of Goué, Pindga, Loumbila, and Ouahigouya, respectively. Small differences were observed among slope values suggesting a certain homogeneity for all tested populations to abamectin. There is no risk of treatment failure with this molecule. LC50 values associated with chlorpyrifos-ethyl from all *T. absoluta* populations do not differ significantly from each other. LC50s ranged from 254.5 to 458.6 mg.L^{-1}, which is lower than 0.4% of the recommended dose, suggesting that the four populations are sensitive to this molecule with limited risk of treatment failure. Spinosad LC50 values were all statistically similar, and were 0.55, 0.44, 0.39, and 0.33 mg.l^{-1} for the populations of Goué, Loumbila, Pindga, and Ouahigouya, respectively. Slight slope variation (1.01–3.49) also indicates a homogeneous response of all four populations. At the dose recommended by the manufacturer very limited treatment failure should be observed.

Cypermethrin (LC50 = 523.3 mg.l^{-1}) and λ-cyhalothrin (LC50 = 411.4 mg.l^{-1}) could only be tested against *T. absoluta* from Goué, whereas deltamethrin was evaluated against insects from Goué (LC50 = 178.2 mg.l^{-1}) and Ouahigouya (LC50 = 116.1 mg.l^{-1}) only. Control failure probabilities of 80%, 79%, and between 51% and 66% were measured for cypermethrin, λ-cyhalothrin, and deltamethrin, respectively. For these three active molecules, the calculated slopes are similar (0.003–0.005) suggesting that a large increase of insecticide concentration is required to reach a small increase in larval mortality. *Bacillus thuringiensis* LC50 values ranged from 6.99.106 IU.l^{-1} (Pindga population) to 68.58.106 IU.l^{-1} (Ouahigouya population). For the populations of Pindga, Goué and Loumbila, there is a very limited risk of control failure, which is not the case for the population of Ouahigouya where there is a 30% chance of treatment failure. The calculated slopes and resistance ratios suggest that the population of Ouahigouya is expressing a higher level of resistance that the other three populations.

Table 5: Susceptibility of different *T. absoluta* populations from Burkina Faso to the most commonly used insecticides in the country. LC are expressed in mg.l^{-1} except for *Bacillus thuringiensis* were million unit.l^{-1} are used.

Insecticide	Population	N	LC50	Confidence	LC80	Confidence	Slope ± SE	χ2	Control failure	RR
Acetamiprid	Pindga	192	455.8	355.0–710.5	727.0	546.9–1224.2	0.003 ± 0.001	1.26	85	1.3
	Goué	192	485.6	337.9–1151.4	829.0	558.6–2256.3	0.003 ± 0.001	0.86	79	1.4
	Loumbila	192	340.5	254.8–522.6	610.6	459.8–1134.3	0.003 ± 0.001	0.07	72	1
	Ouahigouya	192	363.5	305.7–411.5	507.7	451.5–632.0	0.006 ± 0.002	0.02	91	1.1
Abamectin	Pindga	192	0.3	0.1–0.4	0.7	0.5–1.0	1.83 ± 0.46	5.47	0	1.2
	Goué	192	0.3	0.2–0.4	0.5	0.4–0.7	3.17 ± 0.71	3.53	0	1.5
	Loumbila	256	0.3	0.1–0.4	0.6	0.5–0.8	2.50 ± 0.44	3.21	0	1.2
	Ouahigouya	448	0.2	0.1–0.3	0.6	0.5–0.8	2.58 ± 0.50	1.97	0	1
Chlorpyrifos-ethyl	Pindga	192	458.6	359.3–697.7	895.5	670.4–1678.2	0.002 ± 0.001	0.26	0	1.8
	Goué	192	396.8	311.7–488.9	682.0	565.1–986.2	0.003 ± 0.001	1.79	0	1.6
	Loumbila	192	384.0	305.3–457.3	635.1	544.91–811.7	0.004 ± 0.001	2.51	0	1.5
	Ouahigouya	192	254.5	213.9–305.2	369.6	316.5–461.3	0.008 ± 0.002	2.75	0	1
Spinosad	Pindga	192	0.4	0.3–0.6	1.3	1.0–1.8	2.84 ± 0.57	3.19	0	1.3
	Goué	192	0.6	0.5–0.6	0.8	0.7–0.9	3.49 ± 0.12	6.97	0	1.3
	Loumbila	192	0.4	0.0–0.6	0.8	0.6–1.0	1.01 ± 0.22	1.17	0	1.2
	Ouahigouya	192	0.3	0.1–0.6	0.9	0.6–1.7	1.52 ± 0.51	1.54	0	1
Bacillus thuringiensis subsp. Kurstaki	Pindga	192	7.0	5.6–8.0	10.6	9.5–12.6	0.23 ± 0.01	0.22	0	1
	Goué	192	18.9	12.4–26.7	37.1	28.9–51.9	0.05 ± 0.01	2.88	0	2.7
	Loumbila	192	8.4	7.3–9.6	12.5	11.1–14.7	0.21 ± 0.01	0.95	0	1.2
	Ouahigouya	192	68.6	46.0–95.1	135.9	106.1–206.3	0.013 ± 0.005	3.33	30	9.8
Cypermethrin	Goué	192	523.3	407.3–891.0	881.8	649.1–1743.4	0.003 ± 0.001	2.79	80	1
λ-Cyhalothrin	Goué	192	411.4	304.4–1207.0	733.2	505.8–3131.9	0.003 ± 0.002	0.12	79	1
Deltamethrin	Goué	192	178.2	121.0–223.1	339.8	292.9–404.9	0.005 ± 0.001	4.91	66	1.5
	Ouahigouya	192	116.1	13.3–220.5	291.1	200.9–1364.5	0.005 ± 0.001	1.6	51	1

N = number of tested larvae; LD = Lethal dose; SE = standard error of slope; χ2: Chi-square testing linearity of dose–mortality response; resistance ratio (RR) is the quotient of the LC50 value of different populations on the value of the population with the smallest LC50 value.

4 Discussion

The first African countries to declare the presence of *T. absoluta* were Tunisia, Algeria and Morocco, during the 2007–2008 tomato growing season (Mansour et al., 2018). Then, the pest has quickly invaded other Mediterranean countries including Egypt and Libya in 2009. Using a CLIMEX model, Tonnang et al. (2015) portrayed Sub-Saharan Africa as a region of high risk of invasion and establishment of *T. absoluta*. And these predictions were quickly confirmed, as *T. absoluta* has established in Nigeria (2015), South Africa (2016), and Mozambic (2016), just to name a few (Mansour et al., 2018). In Burkina Faso, the pest was first reported in 2016 but local farmers state that the pest was established several years earlier (Son et al., 2017a). The spread of *T. absoluta* to Burkina Faso could be the consequence of adults' natural dissemination, or import from neigh boring affected countries of vegetables carrying larvae or eggs (Verheggen & Fontus, 2019). Based on the results of this study, we raise the hypothesis that all populations found in Burkina Faso originate from a single African area (Guedes & Siqueira, 2012). Indeed, we compared the insecticide resistance of four populations collected at distant locations of Burkina Faso and we could not identify significant differences among these populations in terms susceptibility to the different tested insecticide formulations (Resistance rations RR ranged typically between 1 and 2). However, the specific data obtained from the *B. thuringiensis* treatments do not support fully that hypothesis, but rather suggest that the population of Ouahigouya could have a different origin (The calculated RR of the Ouahigouya population is 9.81). Moreover, the chemical insecticides to which the insects were resistant to are commonly used to control *T. absoluta* in Sub-Saharan Africa (Mansour et al., 2018). The LC50 values are typically used to compare susceptibility of target populations, whereas calculated slopes inform us about the amount of active ingredients needed to increase the biocidal efficacy. Based on the generated values of LC50 and slopes, we can identify three groups of active substances:

(1) With high LC50 values (ranging from 100 to 600 mg.l^{-1}) and low slope values (<0.01), acetamiprid, deltamethrin, λ-cyhalothrin, and cypermethrin belong to the first group of insecticides against which *T. absoluta* show some levels of resistance with a control failure likelihood between 51% and 91%. This is coherent with the low level of efficacy reported by the local producers during our insect collection. Earlier evidences of the inefficiency of some of these chemicals were reported around the globe, and since 1980 in Bolivia (Moore, 1983).

(2) The insecticides of our second group, comprising chlorpyriphos, spinosad, and abamectin, are considered efficient to control *T. absoluta* populations from Burkina Faso without significant risk of control failure. Spinosad and abamectin show low LC50 values (<0.60 $mg.l^{-1}$) and high slope values (>1.0). Similar LC50 values were obtained for abamectin in Turkey and Brazil (Barati et al., 2018a; Konus, 2014; Silva et al., 2011; Silva et al., 2016b; Siqueira et al., 2001) and for spinosad in Iran, Greece, Spain, Brazil, and Turkey (Barati et al., 2018b; Campos et al., 2015a; Roditakis et al., 2017a; Silva et al., 2016; Yalçin et al., 2015). The relatively lower expression of resistance against abamectin could be explained by the fact that this product is used at lower doses in the field, is typically used to control mites and is more rapidly degraded in the environment with low bioaccumulation (Clark et al., 1995). However, based on a rapid survey we performed during our samplings, farmers now started using extensively these products to control the leafminers, with repeated treatments and unrecommended elevated doses. It would not be surprising to see in close future the emergence of resistance, as observed in Europe (Roditakis et al., 2013a, 2013b; Yalçin et al., 2015). Regarding chlorpyrifos-ethyl, observed LC50 are similar to those obtained in Greece and Brazil where the populations were considered sensible (Campos et al., 2014; Haddi et al., 2017; Roditakis et al., 2013a, 2013b).

(3) Finally, the microbiological insecticide *Bacillus thuringiensis* showed contrasted results among the surveyed populations, with LC50 ranging from 7 (Pindga population) to 69 $UI.l^{-1}$ (Ouahigouya population). Low slopes values were also observed for the populations expressing higher LC50 values (Ouahigouya and Goué) with a Control failure likelihood equal to 30% for the population of Ouahigouya, suggesting that these populations express higher levels of resistance against this biological product. The likely explanation for this resistance is that after the discovery of *T. absoluta* in 2016 in Ouahigouya,

Bt pesticides were recommended to growers in that locality. This molecule has been used so abusively that there has even been a rupture and an increase in the price of the product on the market. The microbial-based insecticide *B. thuringiensis* was reported efficient in the North of the African continent, especially in Egypt and Tunisia (El-Aassar et al., 2015; Grissa-Lebdi et al., 2011). The same range of LC50 values were associated with Bt-sensitive populations in Iran and Brazil (Barati et al., 2018b; Silva et al., 2011). But multiple insect species, including *T. absoluta*, have developed a resistance to *B. thuringiensis*, especially Lepidopterans, thanks to a mutation in the membrane transporter ABCC2 (Baxter et al., 2011; Moore, 1983).

Previous reports highlighted the need to reinforce preventive measures of control at the borders of the country, to limit the importation and exportation of contaminated fruits and plants (Son et al., 2017b). But the widespread of established populations of the tomato leafminer in Sub-Saharan African countries make the few existing preventive measures obsolete. It now seems much more important to protect the incomes of local farmers by proposing integrated pest management strategies adapted to local socio-economic and technical conditions. Alter- natives to the chemical and biological substances tested in the present study exist and showed efficiency in Africa and outside (Jactel et al., 2019). Biological insecticides should be favoured and included in the IPM program: Spinosad was found effective in the present study, and neem extracts were previously shown effective in controlling *T. absoluta* in Egyptian open-field tomatoes (Khidr et al., 2013). Alternative control measures include pheromone-based mass trapping, insect-proof nets, and the conservation and release of indigenous biological control agents (Caparros Megido et al., 2014; Caparros Megido et al., 2013b, 2013a; Mansour et al., 2018). Among them, numerous *Nesidiocoris tenuis* were observed in the tomato fields during the present study. The opportunity to mass produce and release them should be considered. Finally, one should identify the host reservoir of the leafminer, probably used to survive during crop rotation (Cherif & Verheggen, 2019).

Partie V : Recherche de mesures préventives pour le contrôle de *Tuta absoluta*

Compte tenu de ce qui précède, *T. absoluta* serait présent dans toutes les régions du pays et provoquerait des pertes de rendement importantes. De plus, 100% des producteurs utilisent des pesticides chimiques de synthèse pour lutter contre le ravageur, dont seulement 20% ont recours également à d'autres méthodes de lutte. Compte tenu du danger des pesticides sur la santé humaine, animale et environnementale, il est plus que nécessaire de développer des stratégies de lutte intégrée où l'on utilise des méthodes de lutte qui empêchent la mineuse de coloniser les plants de tomates. Dans une telle stratégie, l'utilisation de pesticides chimiques n'est envisagée qu'en dernier recours, lorsque le ravageur a pu surmonter les stratégies préventives.

Comme stratégies préventives, nous avons découvert *N. tenuis*, un prédateur de la mineuse. Il serait bon de mesurer sa capacité de prédation, de vérifier son niveau de sensibilité aux molécules efficaces contre la mineuse, et de rechercher des stratégies pour le maintenir dans les parcelles de production. Il est également nécessaire de stimuler la croissance de sa population dans les champs de production. Pour cela, nous avons découvert *Gynandropsis gynandra*, une plante potagère comestible qui est bien appétente pour *N. tenuis* et qui pourrait donc servir de stimulateur du prédateur au champ.

La prévention dépend également de la capacité de la plante à résister ou à tolérer les attaques des ravageurs. Celle-ci est liée aux caractéristiques intrinsèques de la plante donc dépend des variétés. Pour cela, nous avons réalisé un criblage variétal afin de sélectionner les variétés capables de contenir les attaques de la mineuse.

La gestion de la mineuse passe également par la création d'un long vide sanitaire permettant une grande réduction des populations du ravageur dans l'environnement de production. Cela nécessite de connaître les plantes hôtes cultivées afin que lors de la rotation des tomates, ces plantes ne soient pas utilisées. Ainsi, toutes les plantes que les producteurs ont mentionnées dans notre enquête pour la situation de référence comme plante de rotation de la tomate ont été utilisées pour vérifier leur capacité à nourrir la mineuse.

Chapter V.1

Nesidiocoris tenuis in Burkina Faso: Distribution, predatory capacity and insecticide sensibility

Chapter V.1: *Nesidiocoris tenuis* in Burkina Faso: Distribution, predatory capacity and insecticide sensibility

This chapter is an adapted version of the article

Mathieu W. SAWADOGO, Elias MANO, Besmer Régis AHISSOU, Irénée SOMDA, Souleymane NACRO, Anne LEGREVE, François J. VERHEGGEN (under revisions). *Nesidiocoris tenuis* in Burkina Faso: Distribution, predatory capacity and insecticide sensibility. Physiological Entomology

Abstract

Tuta absoluta (Lepidoptera: Gelechiidae) is a worldwide invasive insect species, considered a major pest of tomato. It has recently established in Burkina Faso, where chemical control remains the only affordable option to limit damages. *Nesidiocoris tenuis* (Hemiptera: Miridae) is commercialised as a biological agent to control this pest in other parts of the world. But no literature is available on the presence and the distribution of this species in Burkina Faso.

In this study, we first aimed at surveying the presence of *N. tenuis* throughout tomato production areas of the country, and we found it to be present in the entire country.

Then, we evaluated the ability of this beneficial to feed on *T. absoluta* eggs in two distinct experiments: one performed in net cages (involving active foraging), the other one in Petri dish (predator fed ad libitum). All instars preyed on *T. absoluta* eggs, with adults predating up to 45 eggs per day.

Because resistant to agrochemicals populations of *T. absoluta* were recently identified, we finally aimed at identifying active molecules that do not arm *N. tenuis*. We evaluated the toxicity of two synthetic insecticides, three bio-bacterial insecticides and eight plant extracts, all being active ingredients available on the local market. Most of them (i.e. abamectin, emamectin benzoate, spinosad, spinetoram) were highly toxic for both *T. absoluta* and *N. tenuis*. In contrast, biopesticides including *Bacillus thuringiensis*, neem oil, *Cleome viscosa, Ocimum basilicum* and *Cassia occidentalis* were found to be compatible with *N. tenuis* while still controlling of *T. absoluta*. Based on our results, we recommend the application of *Bacillus thuringiensis* to both control *T. absoluta* and protect *N. tenuis* populations.

Keywords: *Tuta absoluta*, *Nesidiocoris tenuis*, biological control, predation, life cycle, tomato, insecticide, Burkina Faso

1 Introduction

Tuta absoluta (Meyrick, 1917) (Lepidoptera: Gelechiidae) is a species of leaf miner native to South America infesting tomato plants and other Solanaceae. It became a worldwide insect pest after invading Europe and Africa (Biondi et al., 2018; Urbaneja et al., 2007). *T. absoluta* was first observed in Northern Burkina Faso in 2016 (Son et al., 2017a). Since then, it has spread to all regions of the country. By undermining the vegetative and reproductive organs, the larvae cause losses of 45-70% to tomato production, the equivalent of 1,650 to 3,300 US\$.ha^{-1} (Sawadogo et al., 2020a). Considering that 167,400 tons of tomato were produced in 2018-2019, representing 20% of the country's vegetables production, the economic damages caused by this pest are potentially huge (MAAH, 2019).

The use of agrochemicals remains the most popular control method. But several cases of treatment failures were recently described, often resulting in the abandonment of farms (Sawadogo et al., 2020b). This situation is the result of the pest ability to develop, along its invasion routes, resistance to most chemical molecules applied in tomato fields (Guedes et al., 2019). As a consequence, farmers increased dosages and frequencies of insecticide applications, reaching up to 40 treatments per crop season (Sawadogo et al., 2020a). In addition to the damage to human health and environment, these practices can devastate the populations of insect beneficials that naturally regulate *T. absoluta* populations in the field.

Several beneficials, including *Nesidiocoris tenuis* (Reuter, 1895) (Hemiptera: Miridae) were observed in tomato fields (Garba et al., 2020; Sawadogo et al., 2020b). *N. tenuis* preferred preys include whiteflies, aphids, thrips and moths, among which important pests like *Spodoptera exigua* Hubner (Lepidoptera: Noctuidae) and *T. absoluta* (Calvo et al., 2009; Gavkare & Sharma, 2017; Urbaneja et al., 2008; Yano et al., 2019). Unlike other members of its family, this zoophytophagous species can hardly survive on tomato in the absence of prey (Mollá et al., 2014). And in that case, it feeds on the plant and causes significant damages (Biondi et al., 2016; Calvo et al., 2009; Kim et al., 2016). In Burkina Faso, *N. tenuis* has been found on various Solanaceae, as well as vegetables of other families including Cucurbitaceae, Asteraceae and Pedaliaceae (Sawadogo et al., 2020b).

The role of *N. tenuis* in controlling *T. absoluta* in Burkina Faso is not documented. Neither is its distribution in the country, despite its potential important role as a biological control agent. In this work, we decided to (i) survey its occurrence in all tomato production areas of the country, (ii) evaluate its predation abilities on eggs using insect populations originating from Burkina Faso, and (iii) evaluate its level of sensitivity to chemical pesticides and biopesticides, and compare them with those of the pest *T. absoluta* in order to identify chemical products that are compatible with an integrated pest management strategy.

2 Materials and methods

2.1 *Nesidiocoris tenuis* distribution in the country

During the two tomato growing periods, ranging from October 2018 to April 2019 and from October 2019 to May 2020, we travelled through all 13 regions of the country to verify presence of *N. tenuis* in tomato fields (figure 21 A). In each visited province (24 of the 45 provinces of the country), at least 6 tomato fields were surveyed, for a total of 165 fields visited. We randomly placed on the field a 1 m^2 quadra (made of four wood sticks) and visually inspected all included plants (figure 21B).

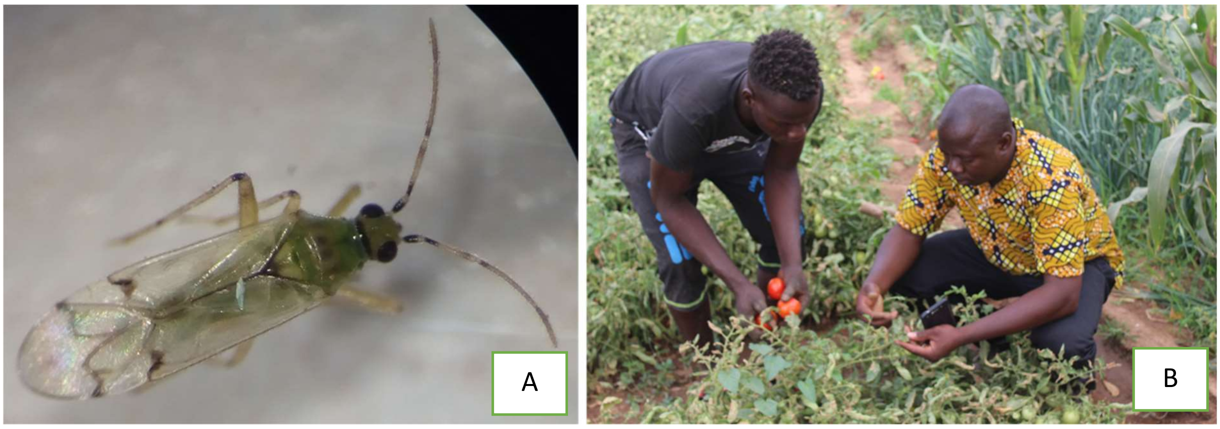


Figure 21: *Nesidiocoris tenuis* (A) and search for *N. tenuis* in the fields (B)

2.2 Insects and plants

Insect and plants were needed for the following laboratory experiments. About 1,000 *T. absoluta* larvae were collected from a tomato field in Kuinima (Bobo-Dioulasso) in March 2020. They were reared in the laboratory, inside cages (80 cm long, 40 cm wide and 40 cm high) placed under a photoperiod of 12:12 (light: dark), 26±2ºC and 71 ± 14% of relative humidity. About 500 *N. tenuis* larvae and adults were collected from a tomato field in Kibi (Bobo-Dioulasso) in April 2020 and brought back to the same laboratory. They were placed in similar cages and were left to reproduce in presence of tomato plants (v. Tropimech) infested by *T. absoluta*. Those plants originated from a greenhouse tomato production.

2.3 Predation capacity

We evaluated the ability of *N. tenuis* to predate on *T. absoluta* eggs through two experiments (figure 22): (i) Predation of eggs performed in Petri dishes (no foraging behaviour needed, ad libitum feeding); (ii) Predation of eggs placed on tomato plants, in net cages (foraging behaviour required).

(i) To expose *T. absoluta* eggs to *N. tenuis*, we introduced 60 eggs in a 8.9 cm⌀ Petri dish containing a slightly moistened piece of blotting paper and a single *N. tenuis* individual (previously starved for 24 hours). After 24h, the predator was removed, and the number of emptied *T. absoluta* eggs was counted using a magnifying glass. The test was repeated five times for each developmental stage of *N. tenuis*, including L1, L2, L3, L4, L5 and adults. Petri dishes containing no *N. tenuis* larvae were used as a control.

(ii) To expose plants covered with *T. absoluta* eggs to *N. tenuis,* we used one-month-old tomato plants. They were introduced into the *T. absoluta* breeding cages to collect eggs. After 24 hours, the plants were removed from the cages. Each plant was carefully examined and *T. absoluta* eggs were counted by two operators to ensure that errors in the counting are reduced at a minimum. If less than *T. absoluta* eggs were counted, the plant was discarded. If more than 60 eggs were found, the plant was used in this experiment. To simulate the field conditions (a density of six tomato plants.m^{-2}), we introduced six tomato plants in a net cage (80 cm long, 40 cm wide and 40 cm high). Two of them were covered with *T. absoluta* eggs, while the other four were “clean” tomato plants (i.e. no insect egg on them). The leaves of all six plants were in contact with each other. A starved predator was introduced into the cage for 24 hours. It was then removed, and non-predated and predated (i.e. emptied) *T. absoluta* eggs were counted. The experiment was repeated five times for each developmental stage of *N. tenuis*, including L1, L2, L3, L4, L5 and adults.

Figure 22: test on the predatory capacity of *T. abslouta* eggs by *N. tenuis*

2.4 Insecticide sensibility

In this assay, two synthetic insecticides, three bio-bacterial insecticides and eight plant extracts were used to evaluate the sensibility of *N. tenuis* and compare it with that of *T. absoluta* larvae. We used the following synthetic single-molecule chemical insecticides: abamectin 18 g L^{-1} EC (Abalone 18 EC, Arysta Lifescience, recommended dose (RD) = 1 $L.ha^{-1}$), emamectin benzoate 19 g L^{-1} EC (Emacot 019 EC, Savana, RD = 0.5 $L.ha^{-1}$), spinosad 480 g L^{-1} SC (Laser 480 SC Dow Agrosciences Export S. A.S, RD = 100 $ml.ha^{-1}$), spinetoram 120 $g.L^{-1}$ SC (Radiant 120 SC Dow Agrosciences Export S.A.S, RD = 100 $ml.ha^{-1}$), *Bacillus thuringiensis* var. Kurstaki 16 000 $IU.mg^{-1}$ (Bio K 16, Savana, RD = 1.5 kg ha^{-1}), Neem oil (Bioprotect, RD = 5 Lha^{-1}), *Jatropha curcas* oil (RD = 5 Lha^{-1}), and botanical extracts of *Cleome viscosa* L. (Cleomaceae), *Parkia biglobosa* Jacq R. Br. ex G. Don f (Fabaceae), *Cassia nigricans* Vahl (Fabaceae), *Ocimum basilicum* L. (Lamiaceae), *Mitragyna inermis* (W.) Kuntze (Rubiaceae) and *Cassia occidentalis* L. (Fabaceae).

The IRAC 022 method was followed (detailed on https://irac-online.org/methods/). We used L2 *T. absoluta* larvae and L5 *N. tenuis* larvae emerging as the first generation of individuals collected in the field. The test consisted of soaking young tender tomato leaves for 3 seconds in one concentration of one insecticide containing Triton X100 wetting agent (0.2 gL^{-1}) and letting them dry up in the open air. A control treatment without insecticide (distilled water + Triton X100) is used to record natural mortalities. At least four different concentrations per product were considered. After drying, leaves were placed in Petri dishes covered with slightly dampened blotting paper. Each box received between five and six larvae of *T. absoluta* or four larvae of *N. tenuis*, reaching a total of 20 *N. tenuis* larvae and *T. absoluta* 32 larvae per concentration of each insecticide. These boxes were then sealed with parafilm. During the following 72 hours, larvae were observed and considered dead when they failed to perform a coordinated movement with the stimulus of a fine tweezer. Insect mortalities were corrected according to Abbott's (1925) formula and the bioassays selected were those where the mortality of the controls did not exceed 10-15%. Probit dose-response analyses were then performed to achieve estimates of lethal concentrations of each insecticide. Control failures likelihood using the Guedes (2017) formula were finally calculated.

$$CFL = 100 - \frac{Mo(\%)}{\mathrm{Ho}(80\%)} * 100$$

CFL (Control failure likelihood) is the probability of treatment failure; Mo is the percentage of individuals that die when the recommended dose is applied; Ho is the minimum efficacy threshold required to allow registration of a conventional insecticide and is generally estimated at 80%.

3 Results

3.1 *Nesidiocoris tenuis* distribution and density in the country

N. tenuis was found in all surveyed areas of Burkina Faso (Figure 23). Their density varies from one field or site to another. Despite the high frequency of low densities (less than 10 individuals/per m^2) encountered, we note that in several fields with lower pesticide use, densities of up to 79.8 ± 9.9 individuals/per m^2 have been recorded in the locality of Tolotama (Bobo-Dioulasso) (figure 23).

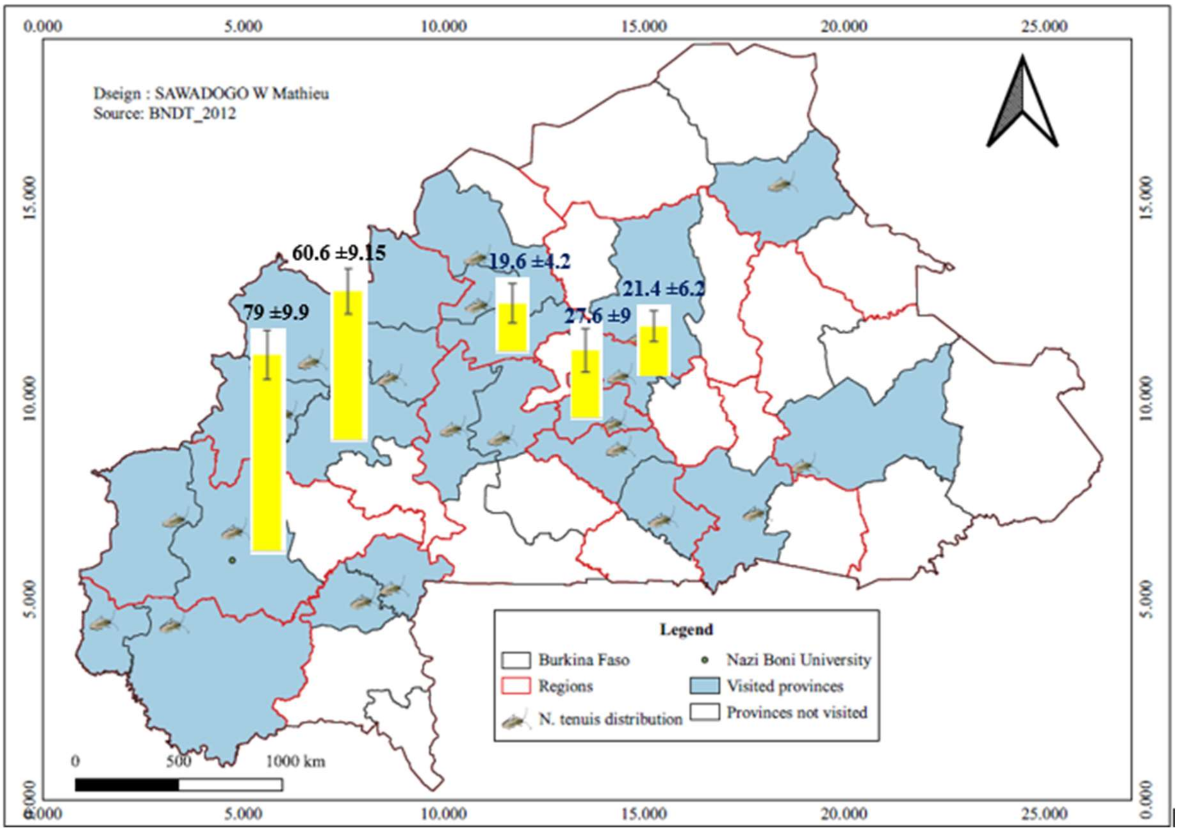


Figure 23: Geographical distribution and high frequency of *N. tenuis* in Burkina Faso

Apart from the localities where we have mentioned the histograms, in the other provinces we found densities of *N. tenuis* below 10 individuals.m^{-2}.

3.2 Predation capacity of *N. tenuis* on *T. absoluta* eggs

All developmental stages of *N. tenuis* consumed *T. absoluta*'s eggs (Table 6). The number of eggs consumed increased with development stage, as confirmed from both experiments (eggs exposed in Petri dish or in net cages).

Table 6: Predation capacity of *T. absoluta* eggs by the six development stages of *N. tenuis*.

Stages	Petri dish experiment	Cage experiment
L1	18.40 ± 12.68 **a**	4.60 ± 5.07 **a**
L2	30.20 ± 8.13 **ab**	9.80 ± 6.49 **ab**
L3	32.40 ± 7.63 **ab**	8.80 ± 5.71 **ab**
L4	39.60 ± 8.32 **b**	13.80 ± 9.65 **ab**
L5	39.60 ± 8.29 **b**	21.00 ± 11.07 **b**
Adults	45.00 ± 9.94 **b**	20.40 ± 7.82 **b**
F	**5.098**	**3.46**
Pr > F	**0.003**	**0.017**

Numbers followed by the same letters are not significantly different (SNK test, $\alpha = 0.05$).

3.3 Sensitivity of *T. absoluta* to insecticides

For all tested molecules, the values (responses) predicted by the log (dose)/probit (mortality) model did not differ significantly from the values observed in the bioassays (low values from $\chi 2$ and P value > 0.05). Therefore, we conclude that the probit model is suitable, and its results can be interpreted (Table 7).

(i) Avermectin/milbemycin: The LC50s of abamectin and emamectin benzoate were low: 0.07 mgl^{-1} and 0.02 mgl^{-1}, respectively. The confidence limits of the LC80 were 0.157-0.44 and 0.04-0.07, respectively. Since they do not overlap, emamectin benzoate has a higher toxicity than abamectin. A control failure likelihood of 0 was recorded suggesting that at the dose recommended by the manufacturers of these insecticides, the treatment would be 100% effective.

(ii) Spinosyns: The LC50s values of spinosad and spinetoram are low (0.04 mgl^{-1} and 0.08 mgl^{-1}, respectively). The confidence limits of the LC80s do not overlap (0.05-0.08 and 0.23-0.51, respectively). Also, the slope of spinosad is higher than that of spinetoram (31.1±5.0 and 3.6±0.8 respectively) suggesting that spinosad is more toxic to *T. absoluta* than spinetoram. The control failure likelihood is 0 for both molecules, which translates that, at the recommended doses, they would be 100% effective against *T. absoluta*.

(iii) *Bacillus thuringiensis*: The LC50 value is 1606.3 mg.l^{-1} and its confidence limit ranges between 1328.3 and 2060.4. Its slope is low (0.1 ± 0.0) which reflects that a large increase in concentration is necessary to reach a slight increase in mortality. However, its control failure likelihood is 0, suggesting a good efficacy against *T. absoluta*.

(iv) Neem and *Jatropha curcas* oils: The LC50s values are 10.34 mll^{-1} and 7.47 mll^{-1}, respectively. The confidence limits of the LC80s do not overlap (26.3-54.5 and 12.0-18.9, respectively), suggesting that jatropha oil is more toxic than neem oil. The slopes are low (0.01±0.03 and 0.01±0.11, respectively). The probabilities that neem and Jatropha oils are not effective to eradicate *T. absoluta* from fields reach 33.8% and 7.5%, respectively.

(v) Regarding bioinsecticides based on plant extracts they all have LC50s higher than 5,000 mgl^{-1}, except *Ocimum basilicum* and *Cassia occidentalis* (1121 mgl^{-1} and 2958 mgl^{-1}, respectively), reflecting their low efficacy in controlling *T. absoluta*.

Table 7: Susceptibility of *T. absoluta* to the chemical insecticides and bioinsecticides tested

Insecticides	N	LC50	Confidence Level (95%)	LC80	Confidence Level (95%)	Slopes ± SE	χ2	Control Failure Likelihood (CFL)
Abamectin	192	0.07	0.01–0.12	0.22	0.157-0.44	5.53 ± 1.67	0.27	0
Emamectin benzoate	192	0.02	0.01–0.03	0.05	0.04-0.07	23.82 ± 4.35	0.91	0
Spinosad	256	0.04	0.03– 0.05	0.06	0.05-0.08	31.10 ± 5.03	0.25	0
Spinetoram	224	0.08	0.01-0.15	0.32	0.23-0.51	3.62 ±0.78	0.77	0
B. thuringiensis	128	1606.30	1328.30-2060.40	2488.70	2040.88-3419.75	0.1 ± 0.0	0.90	0
Neem oil	192	10.34	1.20-16.83	34.26	26.30-54.512	0.01 ± 0.03	0.71	33.75
Jatropha. curcas oil	160	7.47	5.52-9.67	14.60	12.00-18.90	0.01 ± 0.11	0.40	7.50
Cleome viscosa	96	5479	4264-6664	8648	7371-10691	0.22± 0.04	0.70	
Parkia biglobosa	96	7501	5811-12172	12661	9500-25438	0.16 ± 0.05	0.97	
Cassia nigricans	96	5714	3852-8088	11400	8797-17772	0.15 ± 0.03	0.36	
Ocimum basilicum	96	1121	3733-7211	8351	5951-14602	0.11 ±0.03	0.62	
Mitragyna inermis	96	6844	4089-15057	14190	10017-68909	0.11± 0.05	0.91	
Cassia occidentalis	96	2958	1655-3828	5671	26295-54512	0.31 ± 0.07	0.66	

N = number of tested larvae; LC = Lethal concentration; SE = standard error of slope; χ2: Chi-square testing linearity of dose–mortality response; LC are expressed in mg.l^{-1} except neem et Jatropha oils were ml.l^{-1}.

3.4 Sensitivity of *N. tenuis* to insecticides

Similarly with *T. absoluta* data, we conclude that the Probit model is suitable, and their results can be interpreted (Table 8).

(i) Avermectin/milbemycin: LC50s of abamectin and emamectin benzoate are 1.27 and 0.77 mgl^{-1}, respectively. The confidence limits of the LC80s do not overlap (1.63-2.44 and 1.00-1.63 respectively), reflecting the larger toxicity of emamectin benzoate than abamectin. They have slopes of 1.3±0.2 and 2.0±0.4 respectively, suggesting that small changes in the concentration of each of these products has a drastic effect on *N. tenuis* survival. Control failure likelihood of 0 were recorded: These products would eliminate *N. tenuis* from tomato plots at the recommended dosage.

(ii) Spynosins: Spinosad and Spinetoram have LC50 values of 4.94 and 4.93 mgl^{-1}, respectively. The confidence limits of the LC80s overlap (6.49-11.46 and 6.20-9.35): They have the same degree of toxicity to *N. tenuis*. Slopes of 0.3±0.07 and 0.37±0.08 suggest a small increase in predator mortality requires a large increase in pesticide concentration. Control failure likelihood of 0 were recorded, meaning that these products would kill most *N. tenuis* in the fields.

(iii) A LC50 of 6,627 mgl^{-1} and confidence limits between 5,425.5 and 9,197.19 were observed for *B. thuringiensis*. With a slope of 0.02±0.01, its concentration will need to be drastically reduced to positively increase *N. tenuis* survival. At the manufacturer recommended dose, most *N. tenuis* individuals (67%) would survive the treatment.

(iv) LC50s of neem and *J. curcas* oil reached 107.43 mll^{-1} and 109.22 mll^{-1}, respectively. Overlapping confidence limits were found. Both oils have the same degree of toxicity towards *N. tenuis*. Slopes are also low (0.01-0.02). *N. tenuis* populations would mostly survive in the field following the use of these products (87% and 95% of the individuals, respectively).

(vi) Only the three best bioinsecticides formulated against *T. absoluta* were selected for this test. *O. basilicum* had the lowest lethal concentration (LC50=26234 mg. L^{-1}) while *C. viscosa* and *P. biglobosa* all had LC50>50,000 mg.L^{-1}.

Table 8: susceptibility of *N. tenuis* to chemical insecticides and bioinsecticides tested

Insecticides	N	LC50	Confidence Level (95%)	LC80	Confidence Level (95%)	Slopes ± SE	χ2	Control Failure Likelihood (CFL)
Abamectin	152	1.27	1.05-1.54	1.91	1.63-2.44	1.31 ± 0.23	0.60	0
Emamectin benzoate	152	0.77	0.61-0.97	1.20	1.00-1.63	2.00 ± 0.41	0.60	0
Spinosad	152	4.94	3.82-6.19	7.84	6.49-11.46	0.30 ± 0.07	0.15	0
Spinetoram	152	4.93	4.03-5.87	7.23	6.20-9.35	0.37 ±0.08	0.91	0
B. thuringiensis	132	6627	5425.50-9197.19	9714.88	7776.31-1531.88	0.02 ±0.00	0.60	67
Neem oil	132	107.43	83.04-17.52	174.29	131.68-340.18	0.01± 0.00	0.50	87
J. curcas oil	132	109.22	90.31-147.94	156.95	127.15-240.28	0.02 ±0.00	0.70	95
Cleome viscosa	80	74208	55610- 265693	100628	71480-443199	0.32 ± 0.01	0.42	
Ocimum basilicum	80	26234	20484-51521	36335	27251-85472	0.08 ±0.03	0.36	
Cassia occidentalis	80	53233	43751-225326	68126	52644- 407311	0.057± 0.027	0.78	

N = number of tested larvae; LC = Lethal concentration; SE = standard error of slope; χ2: Chi-square testing linearity of dose–mortality response; LC are expressed in mg.l^{-1} except for neem et Jatropha oils were ml.l^{-1}

4 Discussion

Tuta absoluta is present in all tomato production areas of Burkina Faso, where it causes major damage, leading quantities of farmers to abandon their agricultural activities. Happily, we were able to observe one of its predators, *N. tenuis*, in all areas of the country where tomatoes are being produced. While very few individuals were observed in some provinces, important abundancies (>20 predators per meter square) were also noted in several parts of the country, which is largely sufficient to control even large *T. absoluta* infestations (Oztemiz et al., 2012).

The daily consumption of prey eggs by each *N. tenuis* larval stage observed in the present study was comparable to that of previous ones (Michaelides et al., 2017; Mollá et al., 2014; Urbaneja et al., 2008). We found that the quantities of predated eggs decreased significantly when eggs were exposed on a tomato plant. As suggested by (Bouagga et al., 2018), a starved individual spent a major proportion of its time to feed on plant sap rather than on prey eggs.

N. tenuis has potential to control *T. absoluta* in tomato fields in Burkina Faso. But this will never be the case if synthetic insecticides are being used blindly. For this reason, we evaluated the susceptibility of both *T. absoluta* and *N. tenuis* to the synthetic insecticides commercially available in the local market.

Abamectin, emamectin benzoate, spinosad and spinetoram are effective against *T. absoluta*, confirming previous results (Bala et al., 2019; Michaelides et al., 2019), including those performed in the country (Sawadogo et al., 2020b). To preserve the efficacy of these active ingredients, appropriate resistance management systems must be set up, including rotation of molecules with different modes of action and implementation of alternative means of control (IRAC, 2011). Indeed, these molecules have led to resistant populations in other parts of the world including South America, Europe and Asia (Guedes et al., 2019; Lietti et al., 2005; Roditakis et al., 2018; Siqueira et al., 2001). While effective in controlling *T. absoluta*, we observed that these four molecules would not spare *N. tenuis*. Similar susceptibility results were reported by Kim et al. (2018) and Dader et al. (2019) following greenhouse application of spinosad, spinetoram and emamectin benzoate. At the recommended doses, these authors observed 80% of mortality in *N. tenuis*. In addition, Fernández et al. (2012) observed up to 100% mortality after 72 hours of exposure of *N. tenuis* to abamectin (18 mg.l^{-1}).

Our data on *Bacillus thuringiensis* confirm the high efficiency of this biological product against *T. absoluta*, confirming previous reports (González-Cabrera et al., 2011; Hashemitassuji et al., 2015; Jallow et al., 2018a; Kim et al., 2018). We also found that *B. thuringiensis* would be less toxic to *N. tenuis*, confirming previous greenhouse assays (Kim et al., 2018). Molla et al., (2011) found that the combination of *B. thuringiensis* with *N. tenuis* reduced leaf damage by 97%. The use of *N. tenuis* could even allow the reduction of the number of *B. thuringiensis* applications (Gonzalez-Cabrera et al., 2011).

Neem oil and *J. curcas* oil could regulate *T. absoluta* populations. However, the use of *J. curcas* oil is phytotoxic at only 1 $ml.l^{-1}$ on tomato leaves. Several other studies have also highlighted the efficacy of neem oil in the control of *T. absoluta* (Jallow et al., 2018a; Salem & Abdel-Moniem, 2015). Several other oils including *Elettaria cardamomum* (L.) Maton, (Zingiberaceae) (Chegini & Abbasipour 2017), *Syzygium aromatic* L. (Myrtaceae), *Citrus aurantium* amara (Rutaceae) (Ebadah et al., 2016), *Ocimum gratissimum* L. and *O. basilicum* L. (Lamiaceae) (Yarou et al., 2017) would be effective against *T. absoluta*. Neem and *J. curcas* oil were practically non-toxic to *N. tenuis*. Arnó & Gabarra (2011) showed that neem oil (3 mgl^{-1}) did not cause significant mortalities to *N. tenuis* females and larvae. On the other hand, they observed a reduction of 46% in *N. tenuis* fertility. Soares et al. (2019) have shown the compatibility of lemon oil and oil from *Mentha pulegium* L. (Lamiaceae) with *N. tenuis*, but their efficacy against *T. absoluta* has yet to be demonstrated.

The bioinsecticides, *C. viscosa, O. basilicum, C. occidentalis* were shown here to be more toxic to *T. absoluta* than to *N. tenuis*. Their use could be considered in the control of *T. absoluta* and even in association with *N. tenuis*, pending additional work is performed on their formulation. The extracts of these plants would contain organic compounds toxic to the pests (Mano et al., 2019). Several other plant extracts have shown efficacy against *T. absoluta*. This is the case for *Thymus vulgaris* L. (Lamiaceae), *Argania spinosa* (L.) Skeels (Sapotaceae) (Taadaouit et al., 2011), *Euphorbia guyoniana* Boiss and Reut (Euphorbiaceae) (Dehliz et al., 2017) which are effective against *T. absoluta* larvae; *E. guyoniana* also showed repellent effects against females (Dehliz et al., 2017), extracts of *Piper amalago* L. (Piperaceae) at a concentration of $2mg.l^{-1}$ are more than 60% effective on *T. absoluta* larvae and pupae (Brito et al., 2015).

In sum, our study has shown that *N. tenuis* could regulate *T. absoluta* populations if it is present before egg-laying; It is able to search for and empty the eggs of this insect pest. Although it can be phytophagous, it does not manage to go beyond the L3 larval stage if it is fed exclusively on tomato plants. It is therefore forced to seek out and feed on prey, notably *T. absoluta*. Pesticide sensitivity tests show that the *B. thuringiensis* product is effective against *T. absoluta* and safe for *N. tenuis*.

Chapter V.2

Help your allies defeat your enemy: *Gynandropsis gynandra* a refuge plant that promotes the abundance of the natural enemies of the tomato leafminer

Chapter V.2: Help your allies defeat your enemy: *Gynandropsis gynandra* a refuge plant that promotes the abundance of the natural enemies of the tomato leafminer

Mathieu W. SAWADOGO, Schémaëza BONZI, Besmer Régis AHISSOU, Irénée SOMDA, Souleymane NACRO, Anne LEGREVE, François J. VERHEGGEN (in preparation). Help your allies defeat your enemy: *Gynandropsis gynandra* a refuge plant that promotes the abundance of the natural enemies of the tomato leafminer

Abstract

The tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is a worldwide pest of tomato. In Africa and other newly invaded areas, chemical control remains the only management option, despite the emergence of resistant population. *Nesidiocoris tenuis* (Reuter) (Hemiptera: Miridae) is a polyphagous insect predator, often used as a biological control agent in Europe and America, feed on *T. absoluta* eggs and caterpillars. It is encountered in West Africa, but in too low abundance to control *T. absoluta* populations in tomato fields. Through laboratory and field experiments, we evaluated the ability of the African Spiderflower, *Gynandropsis gynandra* (L.) Briq. (Capparaceae), to promote the abundance of *N. tenuis* and control infestations by *T. absoluta*.

In the laboratory, we first highlight that *N. tenuis* can complete its development cycle in 24.1±1.5 days while feeding on *G. gynandra*. Tomato is a poorer host, as this zoophytophagous species could not reach the 4th nymphal stage. We also found that *G. gynandra* is not a suitable host plant for *T. absoluta*.

We then set a field assay in two distinct tomato producing areas in Burkina Faso, where five different tomato-*Gynandropsis* associations we set up, in absence of any other mean of pest control. The abundance of *T. absoluta* and *N. tenuis* was monitored during 12 weeks on both plant species. High densities of *N. tenuis* (between 2 and 10 individuals per plant) were recorded in all tested tomato-*Gynandropsis* associations, while *T. absoluta* were barely never detected.

G. gynandra would interfere little or not at all with tomato production as we found no difference between the production of the plants in association culture and those grown in pure ($p=0.12$). Our fruit yields (26.9 $T.ha^{-1}$ -38.1 $T.ha^{-1}$) are well above the national yield of 21 $T.ha^{-1}$.

Keywords: *Cleome gynandra*, *Tuta absoluta*, *Nesidiocoris tenuis*, whitefly, tomato, intercropping.

1 Introduction

The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), has become a worldwide pest of tomato in almost all continents (Desneux et al., 2011; Verheggen & Fontus, 2019). In Burkina Faso, it has been threatening the tomato sector since its arrival in 2016 (Son et al., 2017a). Yield losses of 45-70% are often recorded, with some severe infestations leading to complete destruction (Sawadogo et al., 2020a). To ensure the protection of their crops, farmers are exclusively using synthetic pesticides, often experiencing treatment failures resulting from the emergence of resistant populations (Sawadogo et al., 2020a, 2020b). In addition to the health consequences for humans, the misuse of these hazardous chemicals has had disastrous consequences for non-target organisms, including naturally occurring beneficials (Campolo et al., 2017; Martinou et al., 2014).

Among the most efficient and abundant natural enemies of the tomato leafminer is *Nesidiocoris tenuis* Reuter (Hemiptera: Miridae). It is found in all climatic zones of the country and is especially associated with vegetable fields (Garba et al., 2020; Sawadogo et al., 2020b). *N. tenuis* is a zoophytophagous bug, which has adapted to *T. absoluta* by preferentially predating eggs and early larval stages (Dhanapal et al., 2021; Urbaneja et al., 2008). As a generalist species, it also predates whiteflies, thrips, aphids, spider mites and Lepidoptera species (Perdikis & Arvaniti, 2016; Soares et al., 2019; Urbaneja et al., 2012, 2008). In the absence of prey, it feeds on plant sap, causing production losses but also promoting plants natural defences to pests (Biondi et al., 2016; Naselli et al., 2016a, 2016b; Pérez-Hedo et al., 2015). Plants such as *Sesamum indicum* and *Dittrichia viscosa* are preferred hosts of *N. tenuis*. Their association with tomato cultivation reduces the damage of the predator on tomato (Biondi et al., 2016; Naselli et al., 2016b).

We recently found that *N. tenuis* could be extremely abundant on the African spiderflower *Gynandropsis gynandra* (L.) Briq (Capparaceae). In tomato growing areas, *G. gynandra* lacking *N. tenuis* were difficult to find. *G. gynandra* is often considered a weed, but is also used as a medicinal plant, and is sometimes cultivated for its leaves which are used as a sauce in human food (Chweya & Mnzava, 1997; Heuzé et al., 2020; MAHRH, 2007; Onyango et al., 2013).

Here, we decided to evaluated the potential of *G. gynandra* in intercropping with tomato plants to increase the abundance of *N. tenuis* and protect tomatoes from *T. absoluta* infestations. We started with several laboratory assays dedicated to verify whether *G. gynandra* allows the complete development of *T. absoluta* and *N. tenuis*. Then, we performed field assays where tomato and spiderflower were associated, and we evaluated the abundance of leafminers and natural enemies in on both plants, along with the resulting tomato yields.

2 Materials and methods

2.1 Insects

T. absoluta larvae and *N. tenuis* nymphs and adults were collected from open tomato production fields in Kuinima (11°12'8"N; 4°17'50"W) in March 2020 and in Kibi (11°12'13"N; 4°14'47"W) in April 2020, all located in the Hauts-Bassins region in Burkina Faso. These insects were brought back to the laboratory for mass rearing in 80×40×40 cm cages under 26±2°C, 50±15% relative humidity and a 12:12 photoperiod.

2.2 Plant species

Tomato plants (v. Tropimech) were used for feeding *T. absoluta* and inducing oviposition. *T. absoluta*-infested tomatoes were used to feed *N. tenuis*. *Gynandropsis gynandra* (figure 24) plants were grown in ½ litre pots containing sterilised potting soil and were used after 4 weeks in the different laboratory bioassays.

Figure 24 : *Gynandropsis gynandra*

2.3 Laboratory assays

Tuta absoluta eggs were placed on either tomato or spiderflower leaves, and then introduced in Petri dishes containing slightly moistened blotting paper and sealed with parafilm. The emerging larvae were monitored twice a day until pupation. This protocol was repeated with *N. tenuis* eggs and larvae. Survival rates as well as egg incubation times, development durations of both insects on tomato and *G. gynandra* were measured.

2.4 Field bioassay

To evaluate the ability of *G. gynandra* to maintain populations of *N. tenuis* in production plots, we set up a trial, from early January to late April 2021, in two tomato production sites located in the surroundings of Bobo-Dioulasso (Kodeni: 11°08' 10.2"N; 4°19'08.2"W and Kimidougou: 11°17'48.9"N; 4°14'51.1"W). The two sites are 30 km apart and experience heavy *T. absoluta* infestations each year. For this trial, we used the Mongal tomato variety as well as a locally produced and marketed ecotype of *G. gynandra*. A completely randomised Fischer block design was set up in both locations and included five treatments, replicated four times each. Each "experimental plot" consisted in six rows of 9 plants per row. The treatments are as follows: T1: 6 lines of tomato; T2: 6 lines of *G. gynandra*; T3: 1 line of tomato + 1 line of *G. gynandra* + 1 line of tomato + 1 line of *G. gynandra* +1 line of tomato + 1 line of *G. gynandra*; T4: 2 lines of tomato + 2 lines of *G. gynandra* + 2 lines of tomato; T5: 1 line of *G. gynandra* + 4 lines of tomato + 1 line of *G. gynandra*. Tomato plants were cultivated in a nursery and were transplanted to the field at the age of three week. *G. gynandra* seeds were sown three weeks before tomato transplanting, to allow the establishment of *N. tenuis* before *T. absoluta* in the tomato production. Gravity irrigation and manual weeding were all carried out on demand. A well decomposed manure (20 Tha^{-1}) and NPK (14-23-14) mineral fertilizer (500 $kgha^{-1}$) were added to all experimental plots 13, 30, 50 and 80 days after transplanting. No pesticides were used in this trial.

Each week, for each experimental plot, five tomato and five *G. gynandra* plants were randomly selected per treatment to visually count the number of *T. absoluta* and *N. tenuis* individuals. A total of 80 plants of each species were considered (5 plants/treatment × 4 treatments × 4 replicates) per site to monitor the population dynamics of *T. absoluta* (active and inactive mine) and *N. tenuis*. Observations on the fruits are also made as soon as they appear. Every week, we also monitored the number of fruits, the number of fruits attacked by *T. absoluta*; the mass of mature fruits and the mass of mature fruits attacked by *T. absoluta*.

In terms of data analysis, after checking for normality, an analysis of variance (ANOVA) was used to compare the means of the data that follow the normal distribution, while the non-parametric Kruskal-Wallis test was used to compare the means of those that do not follow the normal distribution. The Student Newman-Keuls (SNK) test and Dunn's test at the 5% significance level were used for pairwise comparison of ANOVA and non-parametric means respectively. The data were analysed with SPSS Statistics 25 and XLSTAT.

3 Results

3.1 Laboratory assays

We found no difference between the number of *T. absoluta* eggs hatched on tomato leaves and on *G. gynandra* leaves (89-90%; K=0.76; P= 0.38). Similar incubation time are also observed: 3.9 ± 0.6 on tomato, 4.1 ± 0.2 on *G. gynandra* (K= 0.06; P = 0.80). As for the survival of L1 larvae, none could survive 72 h on *G. gynandra* while 89% survived on tomato. We collected additional L2 larvae from the tomato rearing and placed them on *G. gynandra* leaves but again, none survived more than 72 h on *G. gynandra*.

The life history traits of *N. tenuis* reared on tomato and on *G. gynandra* are placed in Table 9. We found similar hatching rates on the two plant species (K= 0.21; P= 0.65), as well as similar incubation durations (K=0.012; 0.91). No individual was able to reach the fourth larval stage by feeding exclusively on tomato. The development cycle of *N. tenuis* on *G. gynandra* is 24.1±1.5 days.

Table 9: Average duration (days) of the different development stages of *N. tenuis* on tomato and *G. gynandra*

Plants	N	Hatching rate (%)	Incubation time	L1	L2	L3	L4	L5	Adults	Development cycle	Survival rate (%)
Tomato	44	94	7.5±0.8a	1.2±0.3a	2.3±1.2a	3.1±1.0a	/	/	/	/	0
G. gynandra	20	90	7.6±0.9a	1.5±0.1b	2.2±0.8a	3.1±0.9a	5.2±0.3b	4.3±0.6b	28.1±7.3b	24.1±1.5	77
K		0.21	0.012	17.40	0.21	0.07	25.28	23.61	23.24	23.61	29
P		0.65	0.91	≤0.001	0.65	0.79	≤0.001	≤0.001	≤0.001		≤0.001

NB: Means followed by the same letters in the same column are not significantly different according to the Student-Newman and Keuls test at the 5% threshold. L: nymphal stage; N: number of individuals tested.

3.2 Field bioassay

Despite the attacks of *T. absoluta* in the neighbouring fields of the tomato growers, only a few leaves showing small areas of mining but whose mines are quickly stopped at the beginning were observed in our experimental plots. It should also be noted that we hardly encountered any whitefly, which is one of the main pests of tomato in these two localities.

3.3 Population dynamics of *N. tenuis*

Except on the day of transplanting, when *G. gynandra* plants were already naturally infested by *N. tenuis* while waiting for tomato plants which presumably did not harbour the predator, we found no difference between the number of *N. tenuis* per tomato plant (between 2.7±2.2 and 7.6±5.5) and that per *G. gynandra* plant (3.7±2.7 -8.1±4.0) in all treatments until month 1 ($p \geq 0.05$). At 6th weeks after tomato transplantation (WATT), except in treatment T5 where the number of *N. tenuis* per *G. gynandra* plant (9.3±4.0) was higher than that per tomato plant (5.6±3.1) ($p < 0.001$), the number of *N. tenuis* per plant of both species was the same in the other treatments. At 8th WATT, the number of *N. tenuis* was higher per *G. gynandra* plant (between 9.1±4.4 and 9.9±4.3) than per tomato plant (between 4.3±2.9 and 5.7±3.6) ($p < 0.001$). This was also the case 10th WATT, except in treatment T5 and 12th WATT, except in treatments T3 and T5 where there were as many *N. tenuis* per tomato plant as per *G. gynandra* plant.

Regarding the evolution of *N. tenuis* populations in each species per treatment, it should be noted that the number of *N. tenuis* increased until 4th WATT ($p < 0.001$), and then remained constant until 12th WATT, except on *G. gynandra* plants in T5 where the growth of *N. tenuis* populations went until 6th WATT and then remained constant until 12th WATT (table 10).

3.4 Production estimates

The number of fruits harvested (figure 25) was a function of the area occupied by the tomato so that in treatment T1 harvested more fruit than treatments T4 and T5 which also produced more fruit than treatment T3 ($p < 0.001$) (Table 11). In contrast, in terms of fruit mass, treatment T1 also produced more fruit but there were no differences between the fruit masses by the other 3 treatments (T3, T4 and T5) (Table 11).

3.5 Effect of *G. gynandra* on tomato production

If we report the productions (number and mass of fruits) of tomatoes of the different treatments on the same surface, there is no difference between the productions of all the treatments with regard to the number of fruits (p = 0.07) and for the fruit mass (p = 0.12) (Table 11).

Figure 25 : Tomato production

Table 10: Population dynamics of *N. tenuis* per tomato plant and *G. gynandra* at both sites

Treatment	Speculations	Tomato transplanting	2nd week	4th week	6th week	8th week	10th week	12th week	K	P
T1	Tomate	0 a A	3.5±3.3 B	6.7±5.8 BC	7.0±3.4 ab C	5.7±3.6 a BC	4.1±2.9 a B	4.7±3.6 a BC	88.99	<0.001
T2	*G. gynandra*	3.1±2.4 b A	4.8±5.2 A	8.1±4.0 B	8.5±4.1 ab B	9.9±4.3 b B	9.4±4.1 c B	8.2±4.1 cd B	62.38	<0.001
T3	Tomate	0 a A	2.7±2.2 B	5.7±4.1 C	5.4±3.5 a C	5.0±2.6 a C	4.8±4.5 a BC	5.2±3.3 abc BC	73.76	<0.001
	G. gynandra	3.2±2.7 b A	4.9±3.0 AB	7.7±5.1 BCD	7.9±3.4 ab CD	9.8±3.3 b D	9.0±3.5 c CD	6.5±3.9 abcd BC	61.53	<0.001
T4	Tomate	0 a A	2.9±2.9 B	7.6±5.5 C	6.1±3.9 ab C	5.1±4.4 a BC	4.8±4.4 a BC	5.1±4.1 abc BC	83.29	<0.001
	G. gynandra	3.2±2.6 b A	4.0±4.2 A	7.7±5.5 B	9.1±3.6 b B	9.1±4.4 b B	8.8±3.8 bc B	9.2±4.6 d B	65.98	<0.001
T5	Tomate	0 a A	2.8±2.1 B	6.1±4.0 C	5.6±3.1 a C	4.3±2.9 a BC	6.0±4.1 ab C	4.9±3.6 ab BC	86.16	<0.001
	G. gynandra	3.3±2.7 b A	3.7±2.7 A	5.8±4.2 AB	9.3±4.0 b C	9.3±4.0 b C	8.7±4.2 bc BC	8.1±4.2 bcd BC	70.96	<0.001
K		162.74	13.85	10.15	33.61	77.11	66.79	38.65		
P		<0.001	0.05	0.18	<0.001	<0.001	<0.001	<0.001		

NB: averages followed by the same lower-case letters in the same column are not significantly different; the same is true for averages followed by the same upper-case letters in the same row.

Table 11: Number and mass of fruit produced at both sites

Treatment	Fruit number (ha)	Number of fruits reported to the same area as T1 (ha)	Mass of tomato fruits (T.ha^{-1})	Fruit mass referred to the same surface as T1 (pure tomato) (T.ha^{-1})
T1	826301.0±132555.0 c	826301.0±132555.0	38.1284±10.0443 b	38.1284±10.0443
T3	313928.6±69296.6 a	627857.1± 138593.2	13.4966±4.4835 a	26.9932±8.9669
T4	479736.4±67547.1 b	719604.6±101320.6	20.2100±6.4039 a	30.3151±9.6059
T5	470629.3±99934.3 b	705943.9±149901.4	19.3214±3.9890 a	28.9821±5.9835
F	35.47	2.68	17.85	2.15
P	<0.001	0.07	<0.001	0.12

NB: Means followed by the same letters in the same column are not significantly different.

4 Discussion

N. tenuis, a predator of several economically important tomato pests, including *T. absoluta*, occurs easily in tomato production fields, as well as on *G. gynandra* in Burkina Faso (Biondi et al., 2016; Sawadogo et al., 2020b).

Our study, we found that *G. gynandra* is not a host plant for *T. absoluta*. This plant belongs to the Capparaceae family, no species of which has ever been recorded as a host plant of *T. absoluta* (Cherif & Verheggen, 2019). Cellular structuring, robustness of epidermis, poverty or inability to assimilate nutrients, presence of toxic secondary metabolites, physical barriers can all be assets that a plant possesses to avoid being attacked by herbivores (Awmack & Leather, 2002a; Krechemer & Foerster, 2017a; Pereyra & Sanchez, 2006). Tomatoes are a poor host for *N. tenuis* as they do not allow it to reach the L4 nymphal stage if fed on exclusively. On the other hand, *G. gynandra* would be a preferred host as it allows the predator to complete its cycle. Our results are in line with those obtained by Biondi et al., 2016. These authors believed that tomato would not contain certain proteins that allow the predator to complete its development cycle compared to sesame which allowed the predator to complete its life cycle. This hypothesis was further clarified by (Naselli et al., 2016b) who showed that sesame contains a high level of oxygenated terpenes which are attractants for mirids especially *N. tenuis*. These compounds could be contained in *G. gynandra* which also attracts *N. tenuis*. We measured an average adult life span on *G. gynandra* of 28.1±8.6 days, shorter compared to those obtained by Biondi et al., 2016 where males and females can live between 40 and 60 days feeding on sesame. This difference could be explained by the different rearing conditions, also it could be hypothesized that sesame would contain more nutrients suitable for *N. tenuis* than *G. gynandra*. Sanchez et al., 2009 showed that the incubation time of eggs is 6.3 days at 35°C while our results show an average of 7.6±0.8 days at 26±2°C. This shows that temperature has an effect on the incubation time of eggs but also on the development of the different stages (Yano et al., 2019). The latter have shown that low temperatures slow down its development, especially that of the nymph. Moreover, Mollá et al., 2014 showed that its development cycle is faster when its diet is diversified. Sugar supplementation on tomato plants could reduce phytophagy of *N. tenuis* in the absence of prey (Urbaneja-Bernat et al., 2019).

We did not experience major attack of *T. absoluta* in our production plots despite the high prevalence of this pest in these two sites. This could be explained by the presence and systematic consumption of the pest's eggs by *N. tenuis*. Also, the predator, by preferentially consuming the early larval stages, will not leave any chance of survival to the small larvae from the undetected eggs leading to a systematic decline of *T. absoluta* in the plots (Michaelides et al., 2017; Mollá et al., 2014; Urbaneja et al., 2008). Laboratory, greenhouse and field studies have reported the ability of *N. tenuis* to significantly reduce the population of *T. absoluta* through predation of eggs and young larvae (Abbes et al., 2012a; Chailleux et al., 2013b; Mirhosseini et al., 2020). In the 2010-2011 season, a nursery introduction of *N. tenuis* in Almeria, Spain, resulted in effective protection of 300 ha of greenhouse tomato and the experiment was successfully repeated the following year on 3500 ha (Urbaneja et al., 2012). Doses of 2 adults per square metre (Mirhosseini et al., 2020) in the greenhouse and 8000 individuals per ha or 0.8 individuals per square metre in the field, effectively control *T. absoluta* (Abbes et al., 2012a). The densities we encountered in our trials are much higher than those mentioned above, hence the very good control of *T. absoluta* and whitefly. Growers need to be aware of calendar insecticide treatments because in most cases they carry out an insecticide treatment at most in the first 2 weeks after transplanting the tomato without taking into account the beneficials present. Thus, they create a boomerang effect that is usually in favour of the pest as it has developed resistance to several chemical molecules (Guedes et al., 2019). Thus, according to our investigations in these production sites, all producers consider *N. tenuis* as a pest to be controlled at all costs.

Presumably *G. gynandra* does not interfere with tomato production as evidenced by the lack of differences in the number and mass of fruits produced by tomato plants grown pure and those grown in association with *G. gynandra*. Having roughly the same habit as tomato, it would produce little or no shade effect or competition for nutrients.

Presumably, *G. gynandra* interferes little or not at all with tomato production, as shown by the absence of differences in the number and mass of fruits produced by tomato plants grown pure and those grown in association with *G. gynandra*. Thus, we obtained yields (26.9 - 38.1 $T.ha^{-1}$) which are largely superior to the national tomato yield in Burkina Faso which is 21 $T.ha^{-1}$ (MAAH, 2019). Having about the same habit as tomato, it would produce little or no shade effect or competition for nutrients with it.

G. gynandra could therefore play a synergistic role with tomato in pest control because (1) its presence would reduce phytophagy of *N. tenuis* on tomato plants in the absence of prey, (2) the attraction of *N. tenuis* in tomato fields and the low phytophagy would stimulate tomato plants to emit volatile compounds attracting auxiliary especially of whiteflies, (3) would maintain *N. tenuis* in abundance in tomato fields while it could disappear in absence of prey (Biondi et al., 2016; Naselli et al., 2016b).

Chapter V.3

Comparison of life history traits and oviposition site preferences of *Tuta absoluta* for twelve common tomato varieties in Burkina Faso

Chapter V.3: Comparison of life history traits and oviposition site preferences of *Tuta absoluta* for twelve common tomato varieties in Burkina Faso

This chapter is an adapted version of the article

Mathieu W. SAWADOGO, Rémy A. DABIRE, Besmer Régis AHISSOU, Schémaëza BONZI, Irénée SOMDA, Souleymane NACRO, Clément MARTIN, Anne LEGRÈVE, François J. VERHEGGEN (2021). Comparison of life history traits and oviposition site preferences of *Tuta absoluta* for twelve common tomato varieties in Burkina Faso. Physiological Entomology, 1-7. https://doi.org/10.1111/phen.12373

Abstract

The South American tomato pinworm, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), is an economically important insect pest of tomatoes. Since its discovery in Burkina Faso in 2016, the use of synthetic insecticides was favored, with many cases of treatment failure.

In order to explore alternative control methods, we have carried out a screening of the twelve main tomato varieties produced in the country to test two hypotheses: (1) Some tomato varieties are less likely to attract gravid females and be used as oviposition site; (2) Some tomato varieties are less suitable host plants than others as they allow slower development and lead to higher mortality. The tested varieties include Roma VF, Kanon F1, Cobra 26 F1, FBT1, FBT2, FBT3, Raissa F1, Jampackt F1, Mongal, Rio grande, Tropimech and Petomech.

Tuta absoluta fitness was largely impacted by the tomato variety, especially egg incubation time and larval and pupal stage durations. As a result, the total *T. absoluta* lifecycle was slower on Cobra 26 F1 and Kanon F1 (24.6 ± 1.8 and 25.8 ± 3.3 days, respectively) and faster on FBT1 and Rio grande (22.6 ± 3.0 and 22.8 ± 2.6 days, respectively). None of the variety impacted adult lifespan. All varieties were accepted as hosts by gravid females. The number of eggs laid per females was statistically similar (p-value = 0.518) among the varieties, and ranged between 20 and 46 per 72 hours.

We conclude that two varieties, Kanon F1 and Cobra 26 F1, have better abilities to slow *T. absoluta* development. As a consequence, the number of annual generations the pest perform may be reduced, and the probability that a natural enemy finds and kills its prey is increased.

Key words: *Solanum tuberosum*, *Tuta absoluta*, screening, invasive species, Burkina Faso

1 Introduction

The South American tomato pinworm, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a voracious miner species that can develop on several plant families with a preference for Solanaceae, and particularly cultivated tomatoes (Bawin et al., 2016, 2015; Caparros-Megido et al., 2013; Cherif & Verheggen, 2019). All instars feed on the parenchymal tissues of leaves, tender parts of stems including buds, flowers and developing or ripe fruits (Desneux et al., 2010; Estay, 2000). The result is a considerable reduction in the photosynthetic capacity of the plant in case of heavy attacks, malformation, perforation and then rot of the fruits if they are colonized by secondary pathogens. It can therefore cause yield losses of up to 100% if no effective control methods are used (Desneux et al., 2010).

Thanks to its high dispersal capacity, estimated at 800 km per year, *T. absoluta* has become the most important pest of tomatoes in European, South American and Asian countries (Biondi et al., 2018; Han et al., 2019a). Since 2008, it has been spreading rapidly over the African continent, particularly in the Maghreb countries, and was first discovered in Burkina Faso (northern region) in 2016 (Mansour et al., 2018; Son et al., 2017a). Since then, chemical control has been favored, and most reports produced from the Agricultural Ministry describe cases of treatment failures and abandonment of production plots (Sawadogo et al., 2020a; Sawadogo et al., 2020b). This is probably due to the ability of this insect pest to rapidly develop resistance to the different chemical molecules used (Guedes et al., 2019; Roditakis et al., 2018).

The use of resistant or tolerant varieties could be part of an integrated management strategy (Azevedo et al., 2003). Some varieties can reduce the development capacity of the insect pest while requiring no technical skill on the part of the farmer. Resistance can be the result of the plant phyto-hormonal system, triggered when the plant is attacked by herbivores (Erb et al., 2012; Mouttet et al., 2013). This is followed by the production of defense compounds by glandular trichomes and autonomous epidermal protrusions (Mccaskill & Croteau, 1999), such as alkaloids, phenolic compounds and terpenes (Azevedo et al., 2003; Bleeker et al., 2012; Gonçalves et al., 2006). Several of these compounds, including 7-epizingiberene, zingiberene (Azevedo et al., 2003; Bleeker et al., 2012; Lima et al., 2015), acyl sugars (Leckie et al., 2014; Resende et al., 2002) and tridecan-2-one (Leite et al., 2000) increase plant resistance against *T. absoluta*. This resistance is expressed by antixenosis (a deterrent mechanism that prevent colonisation by herbivorous insects), antibiosis (the induction of adverse effects on insect survival and development), and tolerance (the ability of the attacked plant to maintain production) (Leite et al., 2000; Vargas, 1970). Thus, commercial tomato varieties with enhanced abilities to produce these defensive compounds may be more tolerant to leafminer, especially during the reproductive stage of the plant, a critical period of attack by this insect pest (Ullé & Nakano, 1994).

It is in this perspective that we conducted a screening of the main commercial tomato varieties available in Burkina Faso to determine their level of vulnerability to *T. absoluta* infestations. We raised two hypotheses: (1) Some of these tomato varieties are less likely to attract gravid females and be used as oviposition site; (2) Some tomato varieties are less suitable hosts than others as they allow slower development and lead to higher mortality.

2 Materials and methods

2.1 Insects

About 500 larvae were collected in the village of Goué, located in the Central Plateau region where, as in the whole country, the leafminer is controlled with pesticides. They were reared in a laboratory located in Bobo-Dioulasso, for four generations on tomato plants v. Rossol, in net cages (80 cm long, 40 cm wide and 40 cm high) under a 12: 12 photoperiod before being tested (Hasan & Ansari, 2011). The average temperature and relative humidity of the laboratory were measured daily and maintained at 28 ± 3° C and 50 ± 15%.

2.2 Tomato varieties

Twelve tomato varieties were used in this study. They included three varieties developed in the Institute of Environment and Agricultural Research (INERA): FBT 1, FBT2, FBT3, and nine commercially available varieties of which five were hybrids: Cobra 26 F1, Raïssa F1, Kanon F1, Jampakt F1, Mongal, and four were fixed: Petomech, Tropimech, Roma VF, Rio Grande. The major characteristics of these twelve varieties are listed in Table 12.

2.3 Evaluation of *T. absoluta* egg-laying preference

Three weeks after seedlings, plants (10-15 cm high) were transplanted individually into ½ liter pots containing heat-sterilized potting soil and left growing for an additional three weeks in net cages. To evaluate *T. absoluta* egg-laying behavior for each variety, in a cage, one plant of each variety was placed and about 25 females less than 5 days old were released to lay eggs (figure

26). The plants were removed after 72 hours for egg counting for each variety. This operation was repeated 15 times for each variety.

Figure 26 : cage containing 12 plants for laying

2.4 Evaluation of *T. absoluta* development

Tomato plants of the twelve varieties were individually placed in net cages with several *T. absoluta* adults (both sexes) overnight. The next morning, eggs were collected. One single egg was deposited on a tomato leaflet (belonging to the same variety it was laid on), placed in a Petri dish (8.9 cm ⌀) containing a piece of moistened blotting paper. The Petri dish was then sealed with parafilm. At least 50 replicates were performed for each variety.

After hatching, the larvae were fed exclusively with the leaves of the tomato variety on which hatching took place. A new leaf was introduced in the Petri dish daily until pupation. After emergence, adults were kept in the same plastic Petri dish with water. Each insect (egg, larvae, pupae and adults) was observed twice a day (at 8 am and 5 pm).

2.5 Statistical analysis

Normality tests were applied to all measured parameters. The non-parametric test of Kruskal Wallis allowed the comparison of the different varieties. The two-by-two comparison of the rankings of the averages was done using the Dunn method (at 5% significance level). An ascending hierarchical classification (AHC) using the different parameters measured made it possible to classify the different varieties. The graphs and the different analyses were built using R version 3.6.3 and XLSTAT softwares.

Table 12: Characteristics of the twelve tomato varieties used in this study

Variety	Precocity	Production period	Main characteristics	Sources
FBT 1	85	Rainy season	Susceptible to fruit bursts	CEDEAO et al., 2016; Some et al., 2014
FBT 2	75	Rainy season	Good resistance to sunburn and fruit bursting	
FBT 3	70	Rainy season	Good resistance to sunburn and fruit bursting	
Petomech	70-80	Cool and hot dry season	Intermediate resistance to *Verticillium* and *Fusarium*, excellent for preservation.	Kimba et al. 2014
Tropimech	65-70	Cool dry season	Resistance to *Fusarium oxysporum* sp. lycopersici race 0 (Fol 0), Tolerance to *Alternaria alternata* f. sp. *Lycopersici* and	
Cobra 26 F1	65	All season	Tolerant to Tomato Yellow Leaf Curled Virus (TYLCV) and bacterial wilt (*Ralstonia solanacearum*); resistance to Fol.0 and 1 and TMV (0)	
Rio Grande	80	Dry and cool season	Resistance to verticilliosis, resistance to fusariosis	
Mongal	60-65	Very hot, cool and winter season	Very high tolerance to bacterial wilt, resistance to Tobacco mosaic virus (0) (TMV), Fol 0 and 1, *Stemphylium* and root-knot nematodes (*Meloidogyne* spp.).	CEDEAO et al., 2016; Kimba et al., 2014
Roma VF	70-80	Cool or winter season	Resistant to Mildew, *Verticilium* and *Fusarium*, Very sensitive to TYLCV.	
Kanon F1	75-80	Dry and cool season	Intermediate resistance to TYLCV and high resistance to Cucumber mosaic virus (CMV), Fol .0 and 1, TMV and *Verticillium.*	Technisem 2016
Jampakt F1	65-70	Dry and cool season	High resistance to *Verticillium dahliae* race 1, Fol: 1 and *Meloidogyne incognita* (Mi) and *Meloidogyne javanica* (Mj).	NTS 2020
Raïssa F1	65-70	Dry and cool season	Resistant to verticilliosis, FOL 1, nematodes, TMV; Good resistance to bursting	

3 Results

The mean numbers of eggs laid on all tomato varieties were statistically similar among the tested tomato varieties (χ^2 = 10.13 df = 11, *p*-value = 0.518) (Figure 27). We observed an important inter-individual variability, with some laying as few as ten eggs, and others laying as many as 200 eggs.

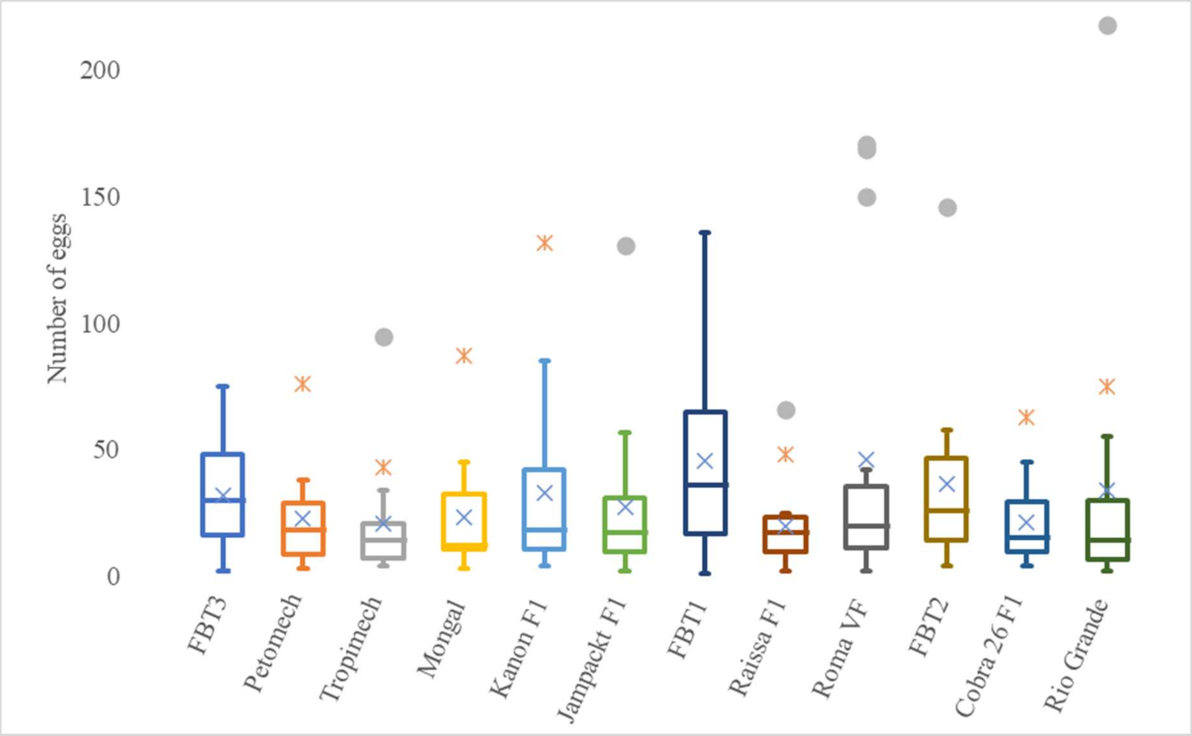


Figure 27: Mean number of eggs laid by *T. absoluta* on twelve tomato varieties

The egg incubation time differed among the varieties (χ^2 = 22.36, df = 11, *p*-value= 0.022) (Table 13), with higher durations observed on Cobra 26 F1, Roma VF and Rio Grande. The average larval development also differed among the tested variety (χ^2= 39. 19, df = 11, *p*-value< 0.001): the longest was recorded on Mongal (12.4 ± 1.5 days), Cobra 26 F1 (12.5 ± 1.1 days) and Kanon F1 (12.7 ± 2.2 days). Similarly, pupal development differed from one variety to another (χ^2= 105.69, df = 11, *p*-value< 0.001). Pupae needed longer period of development on Kanon F1 and Petomech than all the others. Adult lifespan ranged from 9.6 ± 3.6 days on Kanon F1 to 13.2 ± 5.0 days on Rio Grande, but these were not statistically different (χ^2 = 9.51, df = 11, *p*-value=0.575). The average life cycle duration was statistically impacted by the tomato variety (χ^2= 25.32, df = 11, *p*-value=0.008). *T. absoluta* took longer to complete its cycle on the varieties Cobra 26 F1 and Kanon F1 (24.6 ± 1.8 - 25.8 ± 3.3) than on the other varieties.

Table 13: Developmental capacity of *T. absoluta* on 12 tomato commercial varieties in Burkina Faso

Varieties	Number of insects tested	Survival rate %	Incubation time (days)	Larval development (days)	Pupal development (days)	Adult life span (days)	Life cycle duration (days)
Cobra 26 F1	70	68.57	4.2 ± 0.8 bcd	12.5 ± 1.1 ef	8.0 ± 1.5 d	10.5 ± 3.6	24.6 ± 1.8 c
Kanon F1	52	59.62	4.0 ± 0.7 abc	12.7 ± 2.2 ef	9.1 ± 0.8 e	9.6 ± 3.6	25.8 ± 3.3 c
FBT3	50	82	4.1 ± 1.0 abc	11.8 ± 2.8 cdef	7.8 ± 2.0 cd	9.9 ± 3.4	23.7 ± 4.0 a
Jampakt F1	50	68	4.2 ± 1.1 abcd	11.6 ± 1.1 abc	7.8 ± 1.1 d	10.4 ± 4.8	23.6 ± 1.1 ab
Raïssa F1	50	70	4.1 ± 0.9 abcd	12.1 ± 0.4 bcde	7.4 ± 0.7 bcd	10.1 ± 3.2	23.5 ± 1.3 ab
Roma VF	50	74	4.2 ± 0.7 cd	11.5 ± 3.1 cdef	7.6 ± 0.7 cd	10.9 ± 4.7	23.3 ± 3.3 ab
Petomech	55	76.36	3.9 ± 0.7 abc	10.9 ± 1.9 a	8.8 ± 1.3 e	11.0 ± 3.9	23.6 ± 2.0 ab
Mongal	60	80	3.8 ± 0.9 a	12.4 ± 1.5 f	7.1 ± 1.3 abc	9.8 ± 3.1	23.4 ± 1.9 a
Rio Grande	50	72	4.5 ± 1.0 d	11.8 ± 0.9 abcd	6.6 ± 1.5 ab	13.2 ± 5.0	22.8 ± 2.6 a
FBT2	50	72	3.8 ± 0.6 ab	12.1 ± 1.7 def	7.3 ± 0.7 abcd	10.8 ± 4.2	23.3 ± 2.3 ab
FBT1	50	70	4.0 ± 1.0 abc	12.0 ± 2.7 bcde	6.7 ± 1.1 a	10.2 ± 3.7	22.6 ± 3.0 a
Tropimech	55	80	3.8 ± 0.8 a	11.7 ± 0.7 ab	7.5 ± 1.0 cd	10.2 ± 4.8	23.0 ± 1.3 a
K		11.45	22.36	39.19	105.69	0.855	25.32
p-value		0.407	0.022	< 0.001	< 0.001	0.585	< 0.008

A Principal Component Analysis was performed to compare the 12 tomato varieties using the following criteria: number of eggs laid, and the durations of egg incubation, larva development, pupa development, entire life cycle (Figures 28). Based on the PCA, four groups of varieties are identified :

- ➢ The first group includes Kanon F1 and Cobra 26 F1. *Tuta absoluta* lifecycle is slower on both varieties compared to the others;
- ➢ The varieties of the second group, namely Rio grande, FBT1 and Roma VF, have received more eggs during the oviposition assay, and their incubation time was longer;
- ➢ The third group includes Tropimech and Petomech, both characterized by lower numbers of eggs during the oviposition assay, and short life cycle of *T. absoluta*.
- ➢ The fourth group includes FBT2, FBT3, Raissa F1, Jampackt F1 and, Mongal. These tomato varieties were characterized by average features;

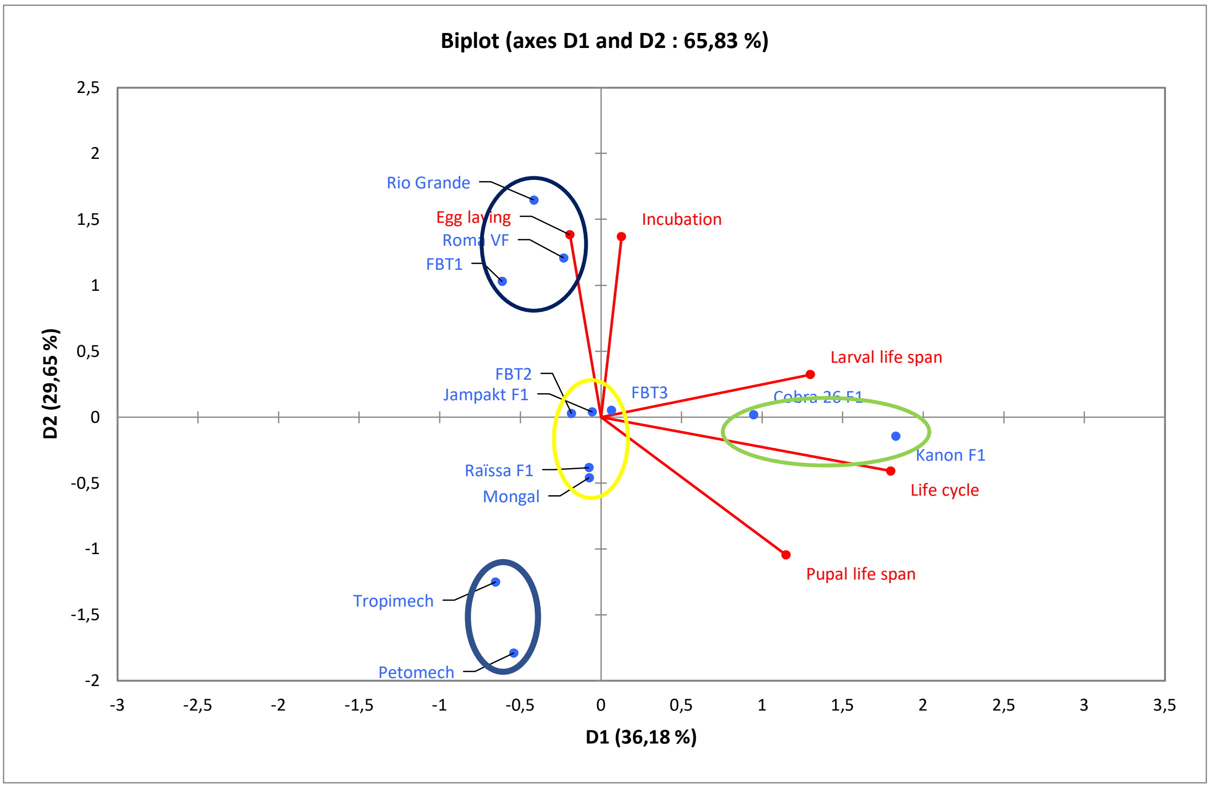


Figure 28: Principal Component Analysis performed on the twelve tomato varieties

An Ascending Hierarchical Classification (AHC) was performed to compare the 12 tomato varieties using the following variables: survival rate, number of eggs laid, and the durations of egg incubation, larva development, pupa development, entire life cycle (Figure 29). Based on the AHC, three groups of varieties are identified:

(i) The first group includes varieties leading to longer life cycle: Cobra 26 F1, Raïssa F1, Jampakt F1 and Kanon F1;

(ii) The varieties of the second group lead to shorter development duration than those of the first group, but faster than those of the third group. It includes Mongal, Tropimech and Petomech.

(iii) The third group includes Rio Grande, FBT2, FBT3, Roma VF and FBT1. These four varieties lead to comparable development durations. Compared to the varieties of the two first groups, they maximize *T. absoluta* fitness.

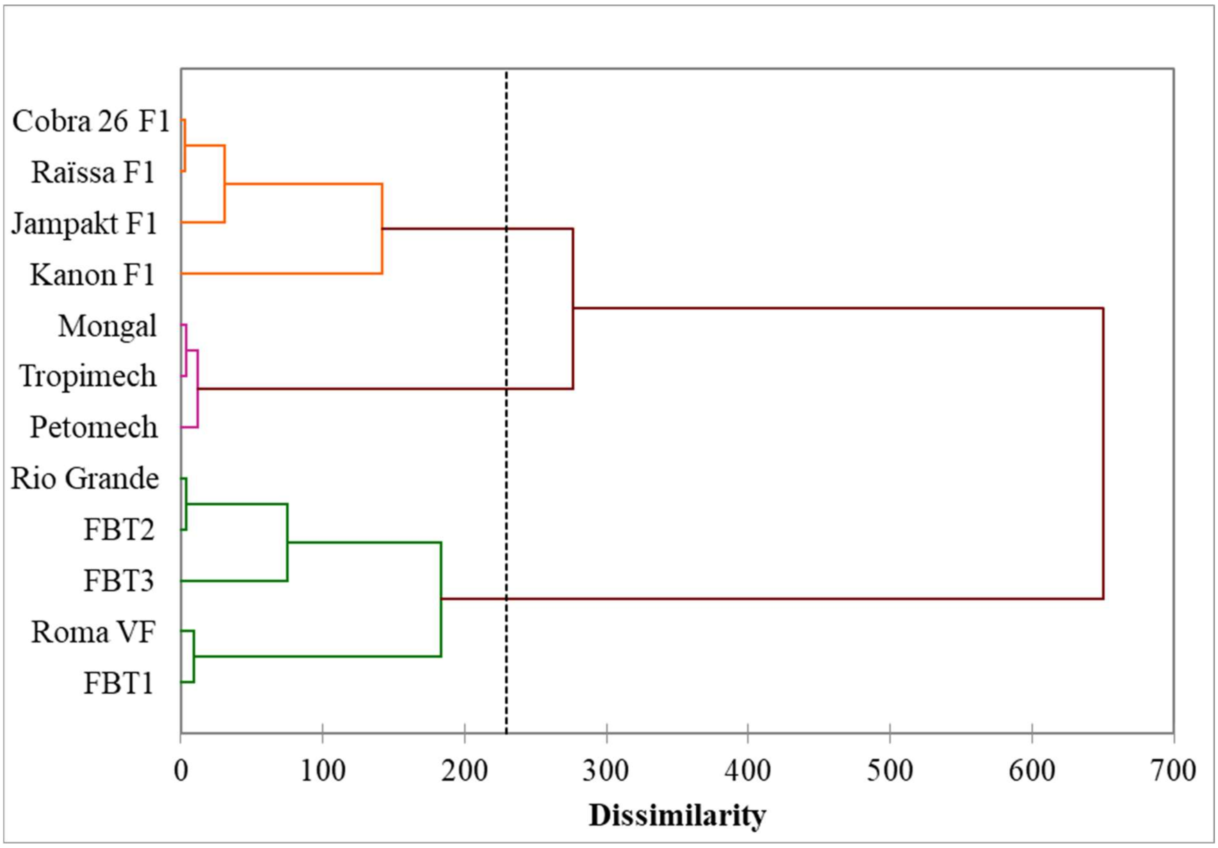


Figure 29: Ascending Hierarchical Classification (AHC) of different varieties.

4 Discussion

We found no difference in terms of number of eggs on the different tested tomato varieties. According to the basic principles of host plant selection, females select their oviposition site to maximize the survivability of their offspring (Gripenberg et al., 2010). *T. absoluta* females are guided by volatile organic compounds released by their host plants and allowing them to discriminate hosts from non-hosts (Caparros Megido et al., 2014; Proffit et al., 2011). They generally lay their eggs on the underside of the apical leaves because of their low calcium content (Cherif et al., 2013; Proffit et al., 2011). The number of eggs they lay are negatively correlated with the presence of compounds such as α-pinene, β-pinene, myrcene and limonene (Yarou et al., 2017), trichome style I on the leaves (Khederi et al., 2014), heptadecane (Suinaga et al., 1999), and zingiberene (Azevedo et al., 2003; Lima et al., 2015). The density and diversity of glandular and non-glandular trichomes may also impact oviposition site preferences (Khederi et al., 2014). Our results suggest that none of the varieties tested produce repellent compounds. They probably did not differ sufficiently in terms of volatile compounds or trichomes architecture or composition. (Bawin et al., 2014) concluded that the oviposition response of *T. absoluta* females is more sophisticated than expected: not just volatile compounds are involved, but also the female previous experience and risk of intraspecific competition. Moreover, we introduced insects in no-choice assays, and preferences may have been highlighted during dual choice experiments. However, field individuals are rarely given the choice among tomato varieties. Our results suggest that any of them is perceived as an adequate oviposition site.

We observed similar survival rates among all 12 varieties suggesting that none of them is genetically armed to counter infestations by the tomato leafminer. The pest has the ability to grow and complete its developmental cycle on all tested varieties. A similar conclusion was drawn by Krechemer & Foerster, (2017) with six different tomato varieties (namely Cherry, Cordilheira, Giuliana, Nemoneta, Paron and Santa Clara). However, we found differences in the duration of embryonic development, larval stage duration and pupal stage duration, resulting in a significant difference in the developmental cycle of *T. absoluta* on the different tomato varieties. Embryonic life span can be influenced by poor feeding of females (Boggs, 1992), reduced moisture at the oviposition site (stomatal closure reducing moisture at the leaf surface or necrosis of the tissue at the site) (Bawin et al., 2015; Woods, 2010), as well as volatile and contact chemicals emitted from the leaves (Bawin et al., 2015; Hilker & Meiners, 2011). The third option would be the most plausible in our study, since all females were fed similarly prior to the experiment, and all plants were exposed to similar laboratory conditions.

Three varieties led to longer larval developmental (Mongal, Cobra 26 F1 and Kanon F1), suggesting poorer nutritional quality and/or production of plant metabolites that impeded larval development (Awmack & Leather, 2002; Bawin et al., 2015; Krechemer & Foerster, 2017; Pereyra & Sanchez, 2006). In addition to the fact that a high C/N ratio in the leaves can lead to a low survival rate and a longer development cycle of the leafminer (Han et al., 2014). Leite et al. (2000) found that higher concentrations tridecan-2-one (produced by type VI glandular trichomes of *Lycopersicon hirsutum*) slowed the development of *T. absoluta* larvae. *Lycopersicon hirsutum* has antixenotic and antibiotic effects against *T. absoluta*. It is more toxic for male larvae than females because of their lower weight and the relatively higher rate of penetration of the allelochemical through the male cuticle, since the latter have a smaller body volume. Zingiberene contained in type VI and IV glandular trichomes (Gonçalves et al., 2006) is also toxic to *T. absoluta* larvae (Azevedo et al., 2003; Lima et al., 2015).

The duration of the biological cycle of *T. absoluta* varied over the different tested varieties (between 22 and 26 days). These values are close to those reported by Razuri & Vargas, (1975) (27 days), Fernández & Montagne, (1989) (24 days) and Cherif et al. (2019) (24.54 ± 2.40 days) for experimental temperatures close to ours (24 and 28° C). Lebdi-Grissa et al. (2011), working on a Tunisian *T. absoluta* strain, under temperature conditions close to ours (25±2°C) reported much longer developmental cycles (i.e. 37 days), including pupal development of up to 14 days, much more than the one we observed in our study (8 days). In herbivorous insects, a shorter development period is a key indicator of a good food quality (Awmack & Leather, 2002; Pereyra & Sanchez, 2006).

Based on our results, we conclude that two varieties available on the Burkinabe market, namely Kanon F1 and Cobra 26 F1, have better abilities to slow *T. absoluta* development. Thus the development cycle of the insect being slowed down, increases the probability that it will be found by a natural enemy (e.g. *Nesidicoris tenuis*) which prefers young larvae (Siqueira et al. 2000b; Urbaneja et al., 2008.

Chapter V.4

Identification of alternative hosts of the tomato leafminer in West Africa

Chapter V.4 : Identification of alternative hosts of the tomato leafminer in West Africa

This chapter is an adapted version of the article

Wendnéyidé Mathieu SAWADOGO, Besmer Régis AHISSOU, Irénée SOMDA, Souleymane NACRO, Anne LEGREVE & François VERHEGGEN. (in press) Identification of alternative hosts of the tomato leafminer in West Africa. African Entomology

Abstract

Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) was introduced in West Africa and since then is becoming a major tomato pest. Various alternative strategies of control have been identified throughout the world, including crop rotation, to deprive the insect of its food. However, this method can only be implemented if a good knowledge of the local host plants of the leafminer is identified. Here, we have assessed leafminer capacity to develop on 27 common vegetable crops in West Africa, including Poaceae, Apiaceae, Convolvulaceae, Amaranthaceae, Malvaceae, Lamiaceae, Cucurbitaceae, Fabaceae, Brassicaceae, Asteraceae, Solanaceae, and Liliaceae.

Outside the *Solanum* genus, leafminer was not able to develop and complete its life cycle. Among the 27 tested plant species, *S. lycopersicum* L. (tomato) is identified as the best host, allowing rapid development (22.2 ± 1.4 days) and a high survival rate (84%). *S. tuberosum* L. (potato) (24.4 ± 0.8 days; 40%), *S. aethiopicum* L. (bitter tomato) (24.3 ± 0.6 days; 52%) and *S. melongena* L. (eggplant) (25.9 ± 1.8 days; 24%) are three other possible hosts. Onion (*Allium cepa* L.) allows larval development but prevents pupation.

A strategy allowing a prolonged absence of the *Solanum* genus in a production area would allow a considerable reduction of leafminer populations.

Keywords: *Tuta absoluta*, vegetable crops, host plants, *Solanum*, development cycle

1 Introduction

The South American tomato leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is an economic pest of tomato, which has been prevalent since the 1960s in South America (Biondi et al., 2018). The larvae feed on all aerial parts of the plant, destroying vegetative and reproductive organs, including fruits, and can cause up to 100% production losses if no effective control methods are used (Desneux et al., 2010; Sawadogo et al., 2020a). After its discovery in Europe (Spain) in 2006 (Urbaneja et al., 2007), it has acquired the status of a global pest of tomato due to its discovery in several parts of the world (Biondi et al., 2018). It reached North Africa in 2008, West Africa in 2012, and the Caribbean in 2018 (Abbes et al., 2012b; Pfeiffer et al., 2013; Son et al., 2017a; Sylla et al., 2017; USDA-APHIS, 2011; Verheggen & Fontus, 2019). This invasion is explained by its high reproductive capacity (multivoltine species that can lay more than 240 eggs per female) (Fernandez & Montagne., 1990; Germain et al., 2009), its expansion rate (800 km per year) (Biondi et al., 2018), ability to easily locate its hosts (Bawin *et al.* 2017) and above all its resistance to several chemical insecticides (Guedes et al., 2019; Han et al., 2019b; Sawadogo et al., 2020b).

Various alternative strategies of control have been identified throughout the world, including tolerant cultivars, beneficial species, entomopathogens, biopesticides, pheromones, and crop rotation (Abd El-Ghany et al., 2018; Cagnotti et al., 2020; Caparros Megido et al., 2013b; Ferracini et al., 2019; Gharekhani & Salek-Ebrahimi, 2014a; Jallow et al., 2020; Ndereyimana et al., 2019b; Ouardi et al., 2012). The latter method consists in depriving the insect of its food by alternating tomato production with other vegetable crops. Such an approach is successfully implemented in some tomato production areas in the USA (Portakaldali et al., 2013; Zalom et al., 2008). However, this method can only be implemented if a good knowledge of the local host plants of the tomato leafminer is identified (Bawin et al., 2016; Cherif & Verheggen, 2019).

The main host plant of the tomato leafminer is tomato (*Solanum lycopersicum* L.), but it has been reported to feed on other solanaceous plants such as potato (*Solanum tuberosum* L.), eggplant (*Solanum melongena* L.), pepino (*Solanum muricatum* Aiton), and black nightshade (*Solanum nigrum* L.). The insect can also feed on other plant families including Amaranthaceae, Euphorbiaceae, Cucurbitaceae, Geraniaceae, Fabaceae, Asteraceae, and Malvaceae where it can complete at least part of its cycle (Abbes et al., 2016; Cherif & Verheggen, 2019; Mohamed et al., 2015; Portakaldali et al., 2013; Sylla et al., 2019; Vargas, 1970).

Sawadogo *et al.* (2020a) identified 27 crops commonly used in rotation or association with tomato. We, therefore, decided to evaluate the ability of the tomato leafminer to develop on these plants species, paying attention to larval and pupal development, as well as survival rates at all stages.

2 Material and methods

2.1 Insects

Three hundred larvae were collected in February 2020 in an open field of tomato located in the village of Goué (12° 35' 45" N and 1° 24' 0" W) province of Oubritenga, in Burkina Faso. We then built a tomato leafminer mass rearing within the Research and Training Centre of the Nazi Boni University in Bobo Dioulasso (11°9'53"N; 4°18'54"W). The insects were carefully contained in cages 80 cm long, 40 cm wide and 40 cm high and fed on Rossol tomato plants. The rearing was carried out under conditions of 28 ± 3° C, relative humidity of 50 ± 15%, and a 12:12 h photoperiod.

2.2 Plant material

Twenty-seven plant species were used in this trial (Table 14). They were produced in a greenhouse in jars containing sterilized soil.

Table 14: List of the plant species used in the study

Family	Species	Varieties	Common names
Solanaceae	*Solanum lycopersicum* L	Tropimech	Tomato
	Solanum tuberosum L	Daifla	potato
	Solanum melongena L	F1 Kalenda	Eggplant
	Solanum aethiopicum L	Meketan	African eggplant
	Capsicum chinense Jacq	Jaune du Burkina	Hot pepper
	Capsicum annuum L.	Yolo wonder	Sweet pepper
Poaceae	*Zea mays* L	FBC6	Maize
	Oryza sativa L	FKR62N	Rice
	Sorghum bicolor (L.) Moench	Kapelga	Sorghum
Amaranthaceae	*Amaranthus* L. sp	Vert de Loumbila	Amaranth
	Amaranthus L. sp	Sauvage	Amaranth
	Spinacia oleracea L.	Local	Spinach
Malvaceae	*Abelmoschus esculentus* (L.)	Indiana	Okra
	Hibiscus sabdariffa L	R 121	Sorrel
Cucurbitaceae	*Cucumis sativus* L	Shalini F1	Cucumber
	Cucurbita pepo L	Medina +F1	Summer squash
	Citrullus lanatus (Thunb.)	Kaolack	Watermelon
Fabaceae	*Phaseolus vulgaris* L	Alyze	Green bean
	Vigna unguiculata (L.) Walp	Komcalle	Cowpea
	Vigna subterranea (L.) Verdc	Konkoumzalem	Potato peas
	Arachis hypogaea L	Fleur 11	Peanut
Apiaceae	*Daucus carota* L	Thema	Carrot
Asteraceae	*Lactuca sativa* L.	Tahoma	Lettuce
Brassicaceae	*Brassica oleracea* L.	F1 KK Cross	Cabbage
Convolvulaceae	*Ipomoea batatas* (L.) Lam.	Nayoumondo-2	Sweet potato
Lamiaceae	*Mentha* L. spp	Local	Mint
Liliaceae	*Allium cepa* L.	Ares	Onion

2.3 Experimental setup

Tomato leafminer eggs were collected from the rearing cages; Five of them were deposited on a soft leaf from an approximately 1-month-old plant of each plant species. The leaf was then placed on moistened blotting paper contained in a Petri dish (8.9 cm diameter). The dish was then closed and sealed with parafilm. For each plant species, twenty-five eggs were used for the test (5 replicates of 5 eggs per replicate). After hatching, the larvae were fed exclusively on the leaves of the species on which they have emerged. Fresh leaves were regularly provided and the boxes emptied of old leaves and excrement. Blotting paper was also moistened on-demand until pupation. After emergence, the adults were kept in the same plastic Petri dishes always moistened without food to evaluate their life span.

When L1 larvae could not develop, we collected L2 and L3 larvae from the tomato leafminer tomato rearing cages to check their ability to use the tested plant species as food and pursue their life cycle. Observations were made each morning and evening with a binocular magnifying glass to record the dates of hatching, pupation, emergence, and death of the adult.

2.4 Data analysis

After checking the normality of the data, we carried out descriptive statistics as well as non-parametric Kruskal Wallis analyses for the comparison of the duration of the different developmental stages of the pest on the different crops. The two-by-two comparison of the rankings of the averages was done using the Dunn method (at 5% significance level). These different analyses were carried out with the software XLSAT and IBM SPSS statistics 25.

3 Results

No plant species prevented the hatching of leafminer eggs. Nevertheless, we found differences in incubation times on the different plants ($k= 256.45$, $p < 0.0001$), which varied from 3.0±0.3 days on *Capsicum chinense* to 4.1 ±0.4 days on *Vigna unguiculata*.

Outside the *Solanum* genus, tomato leafminer larvae were not able to develop and complete their life cycle (Table 15). As for the species of the genus *Solanum*, there was a difference in survival rates, with *Solanum lycopersicum* allowing better survival (84%) than *S. aethiopicum* and *Solanum tuberosum* (40 and 52% respectively). *Solanum melongena* allowed complete development of the tomato leafminer, but with a lower survival rate (24%).

Outside the *Solanum* genus, larvae survived up to three days: from 1.3±0.5 days on *Cucumis sativus* to 2.8 ±0.3 days on *Capsicum annuum*. Larval life span was much higher on *Solanum* species (K= 435.64, p < 0.0001). Inside the *Solanum* genus, larvae had a shorter life span (K=34.54, p < 0.0001) on *S. lycopersicum* (11.4±0.3 days) than on the other three species whose life spans varied from 12.3 ± 0.5 on *S. melongena* to 12.5 ±0.5 days on *S. tuberosum*.

As for the L2 and L3 larvae collected in the tomato leafminer rearing cages and deposited on the leaves of the different species, all of them died in less than 3 days except those deposited on *Allium cepa* where they were able to feed for 7 days without reaching the pupal stage.

The duration of the chrysalis stage was affected by the host plant (K= 25.75, p < 0.0001): shorter on *S. lycopersicum* (6.8±1.0 days) than on the other 3 species of the genus *Solanum* (between 7.9±0.9 and 9.7±1.4 days). Adults fed on *S. lycopersicum* (10.0±4.7 days) lived longer (K= 8.61, p = 0.03) than those fed on the other 3 species (between 6.5±3.9 and 7.0±4.1 days).

The complete life cycle was consequently affected by the host plant (K= 32.32, p < 0.0001) and was shorter on *S. lycopersicum* (22.2±1.4 days) than on the other 3 *Solanum* species (between 24.3±0.6 and 25.9±1.8 days).

Table 15: Development capacities of *Tuta absoluta* on the different crop species

Speculations	Hatching rate (%)	Survival rate (%)	Incubation time	Larval life span	Pupal life span	Adult life span	Life cycles
Solanum lycopersicum	100 e	84 d	4.0 ± 0.6 efg	11.4 ± 0.3 g	6.8 ± 1 a	10.0 ± 4.7 b	22.2 ± 1.4 a
Solanum tuberosum	88 bcde	40 c	4.0 ± 0.2 e	12.5 ± 0.5 g	7.9 ± 0.9 b	7.0 ± 4.1 a	24.4 ± 0.8 b
Solanum melongena	80 abcd	24 b	3.7 ± 0.6 cd	12.3 ± 0.5 g	9.7 ± 1.4 b	6.9 ± 3.4 a	25.9 ± 1.8 b
Solanum aethiopicum	96 de	52 c	4.0 ± 0.2 e	12.4 ± 0.6 g	7.9 ± 0.9 b	6.5 ± 3.9 a	24.3 ± 0.6 b
Capsicum annuum	96 de	0 a	3.7 ± 0.3 cd	2.8 ± 0.3 f	-	-	-
Capsicum chinense	100 e	0 a	3.0 ± 0.3 a	1.9 ± 0.2 cd	-	-	-
Zea mays	80 abcd	0 a	3.4 ± 0.3 bc	2.2 ± 0.2 de	-	-	-
Oryza sativa	68 a	0 a	3.4 ± 0.4 abc	1.9 ± 0.2 d	-	-	-
Sorghum bicolor	72 ab	0 a	4.0 ± 0.2 e	1.5 ± 0.5 a	-	-	-
Daucus carota	92 cde	0 a	4.0 ± 0.2 de	1.4 ± 0.5 a	-	-	-
Ipomoea batatas	96 de	0 a	3.3 ± 0.4 ab	2.1 ± 0.2 d	-	-	-
Amaranthus L. sp	80 abcd	0 a	4.0 ± 0.2 de	1.4 ± 0.5 a	-	-	-
Amaranthus L. sp	88 bcde	0 a	4.0 ± 0.2 e	1.4 ± 0.5 a	-	-	-
Spinacia oleracea	92 cde	0 a	4.0 ± 0.2 e	1.3 ± 0.5 a	-	-	-
Abelmoschus esculentus	76 abc	0 a	3.6 ± 0.3 c	2.0 ± 0.2 d	-	-	-
Hibiscus sabdariffa	96 de	0 a	4.0 ± 0.4 fg	2.8 ± 0.3 f	-	-	-
Mentha L. spp	80 abcd	0 a	3.6 ± 0.2 bc	2.7 ± 0.3 ef	-	-	-
Cucumis sativus	92 cde	0 a	4.0 ± 0.2 e	1.3 ± 0.5 a	-	-	-
Cucurbita pepo	88 bcde	0 a	4.0 ± 0.2 e	1.5 ± 0.5 a	-	-	-
Citrullus lanatus	84 abcde	0 a	4.0 ± 0.2 e	1.3 ± 0.5 a	-	-	-
Phaseolus vulgaris	88 bcde	0 a	4.1 ± 0.2 ef	1.7 ± 0.4 abc	-	-	-
Vigna unguiculata	92 cde	0 a	4.1 ± 0.4 g	2.9 ± 0.2 f	-	-	-
Vigna subterranea	92 cde	0 a	4.0 ± 0.2 e	2.2 ± 0.6 d	-	-	-
Arachis hypogaea	96 de	0 a	4.0 ± 0.2 e	1.7 ± 0.4 ab	-	-	-
Brassica oleracea	96 de	0 a	4.0 ± 0.2 e	2.4 ± 1.5 bcd	-	-	-
Lactuca sativa	88 bcde	0 a	3.6 ± 0.3 bc	2.8 ± 0.3 f	-	-	-
Allium cepa	76 abc	0 a	3.7 ± 0.6 c	2.1 ± 0.2 de	-	-	-
K	46.02	380.50	256.45	435.64	25.75	8.61	32.32
Pr > F	0.009	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.03	< 0.0001

NB: variables sharing the same letter are not significantly different from each other (threshold = 5% according to rankings means of Dunn).

4 Discussion

Only the four commonly cultivated *Solanum* species can host tomato leafminer, allowing the pest to complete its development cycle, with a high survival rate. These results confirm some of those of previous works (Brévault et al., 2014; Caparros-Megido et al., 2013; Negi et al., 2018; Pereyra & Sanchez, 2006; Sylla et al., 2018). We found that species belonging to the genus *Capsicum* (*C. annuum* and *C. chinense*), despite being Solanaceae, are not suitable host plants for this pest. These results contradict those obtained by Portakaldali *et al.* (2013) who found that *C. annuum* was a host plant of the tomato leafminer in Turkey. We confirm previous work on the fact that no plant species belonging to other families than Solanaceae allow the development of the tomato leafminer. The larvae may be unable to mine and feed (cellular structuring of the tissues, and robustness of the epidermis), but other reasons may explain their low survivability, including the poor organoleptic qualities of the tissues, the presence of toxin, and physical barriers constituted by rough trichomes causing wounds on the larvae when they move in search of better areas to mine (Awmack & Leather, 2002; Krechemer & Foerster, 2017a; Pereyra & Sanchez, 2006).

We found a shorter duration of larval development on tomato than on the other 3 *Solanum* tested, which confirms the finding of Negi *et al.* (2018) who also found a shorter duration of the larval stage on tomato than on potato or eggplant. This difference within the same genus could be due to the difference in genetic material (species or even varieties) used. Indeed, even within the same species, genetic variability leads to differences in palatability, nutritional and organoleptic quality as well as the ability to produce toxins to counter pest attacks (Awmack & Leather, 2002; Bawin et al., 2015; Krechemer & Foerster, 2017). Onion, on which L2 and L3 larvae were able to maintain themselves for 7 days without being able to move to pupation, is a poor host. Its nutritional intake is undoubtedly low, or its leaves contain toxic substances whose activity is detrimental in the medium term. Species such as *Nicotiana tabacum* L., *Vicia faba* L., *Malva sylvestris* L. are also mentioned as being able to allow partial development of the tomato leafminer (Abdul-Ridha *et al.* 2012; Bawin *et al.* 2016; Cherif & Verheggen 2019).

Our study did not take into account non-crop species but it appears that several species belonging to the Solanaceae family *Atropa belladonna* L., *Datura stramonium* L., *Datura ferox* L, *Lycium halimifolium* Miller, *Nicotiana glauca* Graham, *Solanum dulcamara* L. *S. nigrum* L. *S. elaeagnifolium* Cav., and *Lycopersicum puberulum* Ph are potential hosts of the tomato leafminer (Bawin *et al.* 2016, 2015; García & Espul 1982). In particular, studies conducted by

Idriss et al. (2020) and Campos et al., (2021) show that the black nightshade *Solanum nigrum* L. allows tomato leafminer to complete its cycle. Compared to tomato, *S. nigrum* lead the leafminer to slightly lower fecundity and longevity. Particular attention should be paid to this plant, especially as it is a perennial and widely distributed plant in Africa.

In a context where (1) vegetable production is market-oriented, (2) it is increasingly subject to economically important pests, (3) the massive use of pesticides increases production costs and considerably reduces producers' earnings, and (4) more and more producers on production sites are organized in groups, associations or cooperatives, it is time to think about pest management on the scale of the production site or basin (MAAH 2019; Sawadogo *et al.* 2020a). This could be a reality in a scenario where producers within their group unanimously choose the crops they will produce at the site or production basin level according to the market and pests. In the case of the tomato leafminer management, where the four *Solanum* crops studied are among the main marketed vegetable crops in the country, their rotations could be at yearly intervals with onion, cabbage (the two most important vegetable crops in terms of production), and okra, which represent a very large market share in all regions of the country (MAAH 2019). Despite the implementation of a rotation system with these crops, special attention based on monitoring of weeds and perennials that act as shelters for the leafminers (e.g. *S. nigrum*) would be welcome to avoid even minimal maintenance of the leafminer.

Parties VI : Discussion générale, conclusion, recommandations et perspectives

Chapitre VI.1

Discussion Générale

Chapitre VI.1 : Discussion générale, conclusion, suggestions et perspectives

1. Discussion générale

1.1. Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso

Le Burkina Faso, avec plus de 80% de sa population travaillant dans le secteur agricole, ne dispose que d'une seule saison des pluies par an pour la production agricole. Ainsi, pour lutter contre la pauvreté et le désœuvrement, le gouvernement et ses partenaires ont travaillé à la mise en place de systèmes de rétention des eaux de surface et de pompage des eaux souterraines pour permettre les activités de saison sèche, principalement dédiées au maraîchage. La mobilisation de l'eau et des terres irrigables étant toujours faible par rapport à la demande (MINEFIDE, 2016), explique la petitesse des champs (entre ¼ et ½ ha par producteur) et le fait que ce sont les hommes (98%) (chef de famille) qui sont tributaires des parcelles de production en saison sèche. A cela s'ajoute la pénibilité de l'irrigation et le manque de moyens financiers pour emblaver de grandes superficies même dans les zones où l'eau n'est pas un facteur limitant à la production agricole (MAH, 2011).

Malgré la grande expérience des producteurs dans la production de tomates (41% des producteurs ont entre 10 et 30 ans d'expérience), l'insuffisance des canaux de diffusion des bonnes pratiques phytosanitaires (PDCA, 2019), ajoutée à leur fort taux d'analphabétisme (incapacité à lire les notices), font que les bonnes pratiques en la matière ne sont pas encore bien respectées. Ceci explique que la protection des cultures chez plus de 80% des producteurs se résume à la lutte chimique sans prendre en compte les autres méthodes de lutte plus respectueuses de l'environnement. Cela a été particulièrement vrai avec l'arrivée de la mineuse sud-américaine de la tomate, où les producteurs ont commencé à abuser des pesticides sans pourvoir, dans certaines situations, l'éradiquer (Sawadogo et al., 2020b).

En dépit des dégâts importants subis par les producteurs de tomates (45 à 70% du rendement et 1 à 2 millions de CFA.ha^{-1}) causant ou aggravant les problèmes sociaux et économiques des populations, la faiblesse du système national de surveillance phytosanitaire n'a pas permis aux autorités administratives et scientifiques de s'apercevoir de ce nouveau fléau et de venir rapidement en aide aux producteurs (selon ces derniers, le ravageur était là 3 ans avant son signalement).

Ainsi, pour permettre aux producteurs d'être plus résilients face aux ravageurs, en plus des stratégies basées sur la rotation et la diversification de la production d'espèces qui ne sont pas de la même famille, la mise en place d'un système d'assurance agricole serait la bienvenue. Ceci est d'autant plus d'actualité dans le contexte actuel de mondialisation où les échanges commerciaux se sont multipliés.

1.2. Dynamiques des populations de *T. absoluta* au Burkina Faso

Le calendrier cultural est un élément très important dans les stratégies de lutte contre les ravageurs dans la mesure où il permet de ne pas faire coïncider les périodes de production avec les périodes propices à la prolifération du ravageur (Abd-Elgawad, 2014). A cet effet, le suivi de la dynamique des populations de *T. absoluta* montre que la mineuse est présente toute l'année, mais que la saison des pluies est très peu propice à sa prolifération (Bacci et al., 2019). Ainsi, certaines zones de production, comme Toussiana dans la province du Houet, ne sont pas encore affectées par la mineuse car la quasi-totalité de la production de tomate est réalisée pendant cette période.

En outre, les densités de la mineuse sont plus faibles pendant la saison sèche froide (octobre-février) que durant la saison sèche chaude (mars-mai). Ceci est dû au raccourcissement du cycle de l'insecte avec l'augmentation des températures et la diminution de l'humidité relative de l'air (Cherif et al., 2019; Cuthbertson et al., 2013). Le raccourcissement du cycle de développement entraîne plus rapidement le départ de nouvelle génération qui pourrait être exponentiellement plus nombreuse que la précédente, étant donné la fertilité de la femelle de la mineuse. Ainsi, afin d'éviter la furie de *T. absoluta*, il serait judicieux de produire les tomates pendant ces deux périodes (saison des pluies et saison sèche). Il faudrait donc développer des stratégies de conservation ou de transformation de la tomate pour approvisionner les périodes impropres à la production.

Étant donné que le nombre d'œufs pondus par *T. absoluta* et donc la taille de la progéniture est fonction du nombre d'accouplements (Lee et al., 2014), à travers cette étude nous pouvons également suggérer l'utilisation de phéromones sexuelles dans une stratégie de lutte intégrée. En effet, il faut noter qu'en période de forte infestation nous capturions plus de 6000 individus par piège et par semaine. Cela pourrait réduire de manière significative le nombre d'accouplement dans la population.

1.3. Capacité de reproduction des populations de *T. absoluta* par parthénogenèse

T. absoluta est connu comme un insecte qui peut se multiplier par parthénogenèse deutérotoque (Caparros Megido et al., 2012). Ce statut reproductif peut être annulé s'il est infecté par la bactérie symbiotique *Wolbachia* (Carvalho et al., 2018). Ainsi, la connaissance de son statut reproducteur reste cruciale dans l'élaboration d'une stratégie d'annihilation des mâles par les phéromones. Ainsi, il ressort de notre étude que les femelles vierges parviennent à pondre environ 1/6 des œufs pondus par les femelles accouplées mais vivent plus longtemps que celles-ci. La transmission verticale de la parthénogenèse a été également vérifiée. Ceci confirme les résultats obtenus par Abbes & Chermiti, 2014 avec des populations Tunisiennes de la mineuse.

Ceci soutiendrait l'hypothèse que les phéromones sexuelles pourraient être efficaces dans le contrôle de *T. absoluta* à travers la technique d'annihilation des mâles en réduisant le nombre des accouplements et donc de la descendance.

1.4. Criblages de biopesticides vis-à-vis de *T. absoluta*

Dans la lutte contre la mineuse, plusieurs biopesticides d'origine végétale ont déjà prouvé leur efficacité (Abd El-Ghany et al., 2018). A cet effet, il était opportun pour nous de vérifier l'efficacité des biopesticides disponibles sur les marchés locaux contre *T. absoluta*. Nos investigations ont montré qu'une augmentation de la dose préconisée par les fabricants des produits est nécessaire pour combattre les œufs ainsi que pour tuer efficacement les larves. Les produits les plus efficaces ont été élaborés à partir d'extraits d'écorce d'*Azadirachta indica* et de *Khaya senegalensis*.

Le marché des biopesticides reste un domaine où de nombreux investissements sont nécessaires. En effet, aucun biopesticide produit dans le pays n'a été pour le moment homologué. En général, les techniques de préparation des biopesticides enseignées aux producteurs manquent de standardisation des formules et de la qualité des intrants, ce qui provoque souvent des problèmes de dosage (surdosage ou sous-dosage) au point que les produits peuvent être perçus comme efficaces ou non. De plus, en cas de sous-dosage, cela peut conduire au développement de résistances aux molécules contenues dans les produits (Guedes et al., 2019) si bien que l'inefficacité de ces derniers poussera les producteurs à se tourner davantage vers les pesticides chimiques synthétiques.

1.5. Résistances aux pesticides chimiques et niveau de sensibilité de *T. absoluta* vis-à-vis des principales molécules homologuées

Compte tenu de la capacité de reproduction de la mineuse, des mauvaises pratiques phytosanitaires (utilisation répétée de molécules ayant le même mode d'action, sous-dosage des pesticides, utilisation de produits non homologués contre la mineuse...) (IRAC, 2018), plusieurs populations de *T. absoluta* (dans son aire d'origine ainsi que dans les régions envahies) ont développé une résistance à plusieurs molécules appartenant à plusieurs familles chimiques, notamment les carbamates, les organophosphates, les pyréthroïdes; les avermectines, les azadirachtines, le *Bacillus thuringiensis*, les benzoylurées, les diamides, les néonicotinoïdes, les analogues de la néréistoxine, les oxadiazines, les pyrroles, les spinosynes, les pyridalyles et les semicarbazones (Guedes et al., 2019; Lietti et al., 2005; Roditakis et al., 2018).

Ainsi, lorsqu'un tel ravageur envahit un nouveau territoire, des recherches doivent être menées pour déterminer quelles sont les molécules efficaces contre lui, sous peine de voir des échecs de traitements, surtout si dans la localité nouvellement introduite toutes les molécules s'avèrent inefficaces. Or, l'un des moyens les plus sûrs d'éviter la surutilisation des pesticides chimiques est de trouver des molécules efficaces contre l'invasion de la mineuse. Par conséquent, notre étude sur le niveau de sensibilité des populations de *T. absoluta* aux pesticides (Sawadogo et al., 2020b) nous a permis d'obtenir une liste positive de molécules pouvant actuellement lutter efficacement contre la mineuse. Il s'agit de l'abamectine, qui a été vulgarisée sur plusieurs sites maraîchers, notamment à Pindga (Kombissiri), où en 2018 *T. absoluta* avait presque totalement anéanti la production de tomates, et qui a pu produire la tomate sans *T. absoluta* en 2019 (nous avons passé plus de 2 heures à fouiller le site et n'avons trouvé que 9 larves de mineuses). Par ailleurs, des molécules comme l'emamectine benzoate s'avèrent très efficaces dans la vallée du Sourou et dans plusieurs autres grands sites de production de tomates. Le spinosad, également très efficace, n'est vraisemblablement disponible que pour les producteurs de coton. *Baccilus thuringensis*, qui est aussi largement utilisé, surtout dans la région du nord, commence à être moins efficace contre *T. absoluta*, car nous avons constaté que le niveau de résistance de la mineuse de cette région (RR= 9,81) était beaucoup plus élevé que dans les autres parties du pays.

Cependant, de bonnes pratiques de gestion de la résistance devraient être mises en œuvre pour éviter la résistance à ces molécules, car déjà cette année il a été signalé une faible résistance des populations de *T. absoluta* de Grèce à l'emamectine benzoate. (Roditakis et al., 2021).

1.6. *Nesidiocoris tenuis* au Burkina Faso : distribution, capacité de prédation, sensibilité aux pesticides et mise en place de stratégies pour son maintien et sa prolifération dans les champs.

N. tenuis, prédateur des œufs (l'adulte peut consommer jusqu'à 45,00 ± 9,94 œufs par jour) et des jeunes larves de *T. absoluta*, a été retrouvé dans toutes les zones agroécologiques du pays avec des densités atteignant 79,8 ± 9,9 individus.m^{-2}. Cela représente un atout considérable pour la lutte biologique non seulement contre *T. absoluta* mais aussi contre des ravageurs tels que les aleurodes qui constituent un problème sérieux dans la culture de la tomate (Biondi et al., 2016; Oztemiz et al., 2012; Son et al., 2018). Malheureusement, nous avons constaté que les pesticides chimiques efficaces contre *T. absoluta*, notamment l'abamectine, l'emamectine benzoate, le spinosad et le spinétorame, annihilent également *N. tenuis* (CFL=0%). Ainsi, les biopesticides à base de *B. thuringiensis*, d'*Azadirachta indica*, de *Cleome viscosa*, d'*Ocimum basilicum* et *Cassia occidentalis* pourraient être utilisés en premier ressort contre la mineuse car ils sont moins nocifs pour *N. tenuis*, et les pesticides chimiques mentionnés ci-dessus ne devraient être utilisés qu'en dernier recours.

Dans la plupart du temps au champ, ce prédateur n'arrive pas à jouer réellement son rôle de régulateur des populations de ravageurs à cause des traitements calendaires des pesticides chimiques de synthèse (les traitements sont généralement effectués très tôt après la plantation de la culture sans même se soucier de la présence d'un ravageur). Cela crée un effet boomerang qui est généralement à l'avantage du ravageur car celui-ci, étant fréquemment combattu, a pu développer une résistance aux pesticides (Guedes et al., 2019). Ainsi, l'avantage conféré au ravageur conduit à des traitements très répétés de sorte qu'à un certain moment, le prédateur disparaît de la culture (Sawadogo et al., 2020a). De plus, par méconnaissance, de nombreux producteurs affirment que *N. tenuis* est un ravageur qu'il faut combattre. Il est donc nécessaire d'effectuer un travail sérieux de vulgarisation de ce prédateur.

Puisque *N. tenuis* ne peut boucler son cycle en consommant uniquement le plant de tomate (il ne peut pas dépasser le stade L3) (Biondi et al., 2016), il s'ensuit que même s'il est dans le champ et qu'il parvient à consommer tous les ravageurs, il disparaîtra. Il était donc nécessaire de rechercher des plantes potagères qui lui permettraient de compléter son cycle s'il s'en nourrissait exclusivement. C'est ainsi que nous avons découvert *Gynandropsis gynandra*, une plante cultivée et utilisée pour la consommation humaine. Nous avons ainsi constaté en laboratoire qu'elle pouvait permettre à *N. tenuis* de compléter son cycle de développement en 24,13±1,5 jours à 26±2°C, 50±15% d'humidité relative et une photopériode de 12 :12.

Pour vérifier sa contribution dans la protection de la tomate, nous avons réalisé un essai en milieu réel où nous avons pratiqué la culture intercalaire. Nous avons constaté que *G. gynandra* n'empêchait pas la production de tomates (jusqu'à 30.3151±9.6059 tonnes.ha^{-1}), que *N. tenuis* était rencontré tout au long du processus de production (2 à 10 individus/ pieds de tomate) et que nous avons obtenu des rendements bien supérieurs à la moyenne nationale (21 tonnes.ha^{-1}) (MAAH, 2019) malgré le fait qu'aucun pesticide chimique ou biologique n'ait été utilisé dans cet essai.

Cette plante pourrait donc être une véritable solution au maintien de *N. tenuis*, à sa multiplication et à la réduction de la phytophagie sur la tomate dans les champs, même s'il n'y a plus de ravageurs à prédater entre-temps. Cependant, les recherches sur sa qualité organoleptique, les odeurs qu'elle émet pour attirer *N. tenuis* et les essais de terrain pour confirmer nos résultats peuvent être poursuivis.

1.7. Criblage de variétés de tomates pour tolérance à la mineuse

La résistance variétale reste un enjeu majeur dans la lutte contre *T. absoluta*. Jusqu'à présent, les essais les plus concluants se sont soldés par des baisses de rendement, ce qui est pourtant un des facteurs les plus importants (Guedes & Picanço, 2012). Néanmoins, certaines variétés, en fonction de leur structure, de leur qualité organoleptique et de leur capacité à produire plus ou moins certaines toxines, seraient capables de réduire les dégâts de la mineuse (Gharekhani & Salek-Ebrahimi, 2014b; Sohrabi et al., 2016). Ainsi, le criblage que nous avons effectué a montré que *T. absoluta* ne préfère pas pondre sur une variété particulière (valeur p = 0,518). D'autre part, nous avons constaté que les larves de la mineuse ont un cycle de vie plus long sur les variétés Mongal, Cobra 26 F1 et Kanon F1 et que pour l'ensemble du cycle de développement, les variétés Cobra 26 F1 et Kanon F1 ont montré une plus grande capacité à ralentir le cycle de vie de la mineuse, indiquant qu'elles ont une meilleure aptitude à mieux contenir les attaques de la mineuse.

D'après nos enquêtes, presque tous les producteurs utilisent des semences de variétés améliorées (Sawadogo et al., 2020a). Cela montre qu'ils reconnaissent les qualités intrinsèques d'une variété à offrir les qualités défensives nécessaires à la plante. Ainsi, une communication sur les variétés qui semblent tolérer les attaques de la mineuse pourrait être un atout dans la lutte contre cette mineuse.

Notre étude qui consistait à collecter des feuilles de tomate et à nourrir la mineuse dans des boîtes de pétri pourrait être poursuivie cette fois-ci en mesurant les paramètres de développement de la mineuse sur des plantes vivantes de ces différentes variétés.

1.8. Identification de plantes hôtes alternatives pour la mineuse des feuilles

La réalisation d'un vide sanitaire est un élément très important qui peut réduire de manière significative les populations de ravageurs dans une localité. Toutefois, cela ne sera efficace que si la présence de plantes hôtes alternatives dans l'environnement est détruite ou évitée. Pour atteindre cet objectif la connaissance des plantes hôtes est plus que nécessaire. De notre étude sur les principales cultures pratiquées sur nos sites maraîchers, il ressort que seules les espèces du genre *Solanum* (tomate, pomme de terre, aubergine et aubergine africaine) ont pu nourrir *T. absoluta*, lui permettant de terminer son cycle de développement (Brévault et al., 2014; Negi et al., 2018). Les autres espèces de la famille des Solanaceae (piment et poivron) n'ont pas pu permettre le développement de la mineuse en conditions de laboratoire, contredisant les résultats obtenus par (Portakaldali et al., 2013). Parmi toutes les autres familles, seule la Liliaceae, l'oignon a pu permettre un maintien partiel de la mineuse sans lui permettre de changer de stade.

Nos résultats peuvent déjà être utilisés pour planifier des activités de rotation des cultures à l'échelle d'un site de production afin de réduire de manière significative les populations de la mineuse. Néanmoins, le contrôle des plantes non cultivées est encore nécessaire pour le succès d'une telle stratégie. Par conséquent, cette étude doit être poursuivie afin de découvrir également les plantes non cultivées capables de permettre le développement de la mineuse. A cette fin, des investigations de terrain devraient être menées, notamment dans les zones où les effets des pesticides empêchent le développement de la mineuse dans les champs de tomates ou dans les zones où les tomates ne sont produites qu'une fois par an, afin de savoir sur quelles cultures la mineuse se maintient pour attendre la production des saisons suivantes.

Aujourd'hui plus qu'hier, le secteur des pesticides devrait être sous surveillance, non seulement parce que d'énormes quantités de pesticides non homologués circulent dans le pays, mais aussi parce que les bonnes pratiques de protection des plantes ne sont pas respectées. Il est vrai que le pays dispose d'une réglementation en matière de protection des végétaux (pesticides chimiques), mais la loi doit être largement connue et il doit exister des moyens d'application et de répression pour réduire le nombre de contrevenants.

1.9 Stratégies de lutte intégrée contre la mineuse de la tomate au Burkina Faso

- A partir des résultats que nous avons obtenus, plusieurs scénaris de protection intégrée de la tomate peuvent être imaginés en fonction de la période de production de la tomate, du stade phénologique de la tomate à partir duquel nous voulons démarrer la lutte contre la mineuse, de la disponibilité des intrants (semences de variétés tolérantes, insecticides biologiques ou de synthèses, etc.), de la présence des ennemis naturels de la mineuse des feuilles, etc. Cependant, la meilleure stratégie intégrée pour gérer efficacement la mineuse serait celle qui empêche son développement au-delà d'un seuil de nuisance économique. Ainsi, une stratégie de gestion intégrée commençant avant l'établissement de la culture serait souhaitable. Comme la majeure partie de la production de la tomate au Burkina Faso a lieu en saison sèche, nous proposons ici, sur la base de nos résultats, un scénario de contrôle qui pourrait aider à contenir *T. absoluta* pendant cette période (figure 30). La gestion de la mineuse doit se faire de manière concertée à l'échelle d'un site de production. La pluie étant un facteur très défavorable pour la mineuse (résultat du chapitre III.1), si tous les producteurs du site décident de ne pas produire de spéculation du genre *Solanum* (hôte potentiel de la mineuse, résultat du chapitre V.4) pendant cette période, cela réduira considérablement les populations de *T. absoluta* sur le site de sorte qu'au début de la saison sèche (octobre), il y aura peu ou pas de population résiduelle de mineuses sur le site. De plus, pendant cette période, les producteurs doivent produire le *Gynandropsis gynandra* pour permettre le maintien et la prolifération de *Nesidiocoris tenuis* dans le site (résultat chapitre V.2).
- Des variétés de tomate tolérantes telles que Mongal F1, Cobra 26 F1 et Kanon F1 (résultats du chapitre V.3) doivent être utilisées et les pépinières devraient se faire dès le début du mois d'octobre pour que toutes les récoltes se fassent avant fin février (période de la campagne sèche où la prolifération de la mineuse est moindre, résultat du chapitre III.1). Les pépinières doivent être infestées naturellement ou artificiellement par *N. tenuis.*
- Pour le maintien et la prolifération de *N. tenuis* (prédateur des œufs de *T. absoluta* et de la mouche blanche, etc.) dans les champs de tomates (résultat du chapitre V.2), deux à trois lignées de cette spéculation pourraient être semées autour de la culture de tomates.

Aussi la tomate pourrait être transplantée dans des couloirs où *G. gynandra* constitue les plantes de haie (deux lignes de *G. gynandra* + 10 lignes de tomate + 2 lignes de *G. gynandra*...).

- Pour proscrire toute intervention phytosanitaire inutile, le suivi de la dynamique des populations de *T. absoluta*, par le dépôt de pièges à eau couplés à des phéromones sexuelles (résultats du chapitre III.1) ou par des observations directes permettant de détecter à l'œil ou à la loupe manuelle, les œufs, les larvaires, les pupes et adultes ou les débuts de mines de feuilles, est nécessaire.
- Ces observations conduiront à l'utilisation de biopesticides à base de *Bacillus thuringiensis*, d'*Azadirachta indica* ou de *Khaya senegalensis* (résultats des chapitres IV.2 et IV.3) dès que des mines actives contenant des neonates de *T. absoluta* seront observées.
- Si, malheureusement, toutes les méthodes préventives / défensives ne parviennent pas à arrêter la prolifération de la mineuse des feuilles, les traitements à l'abamectine, à l''emamectine benzoate, au spinosad, au spinétorame ou au chlorpyrifos éthyle pourraient être réalisés uniquement sur les plants de tomate en évitant qu'une grande quantité de bouillie n'atteigne les plantes de *G. gynandra* par dérive. Cela contribuera à préserver les populations de *N. tenuis* dans la parcelle de production de tomate.

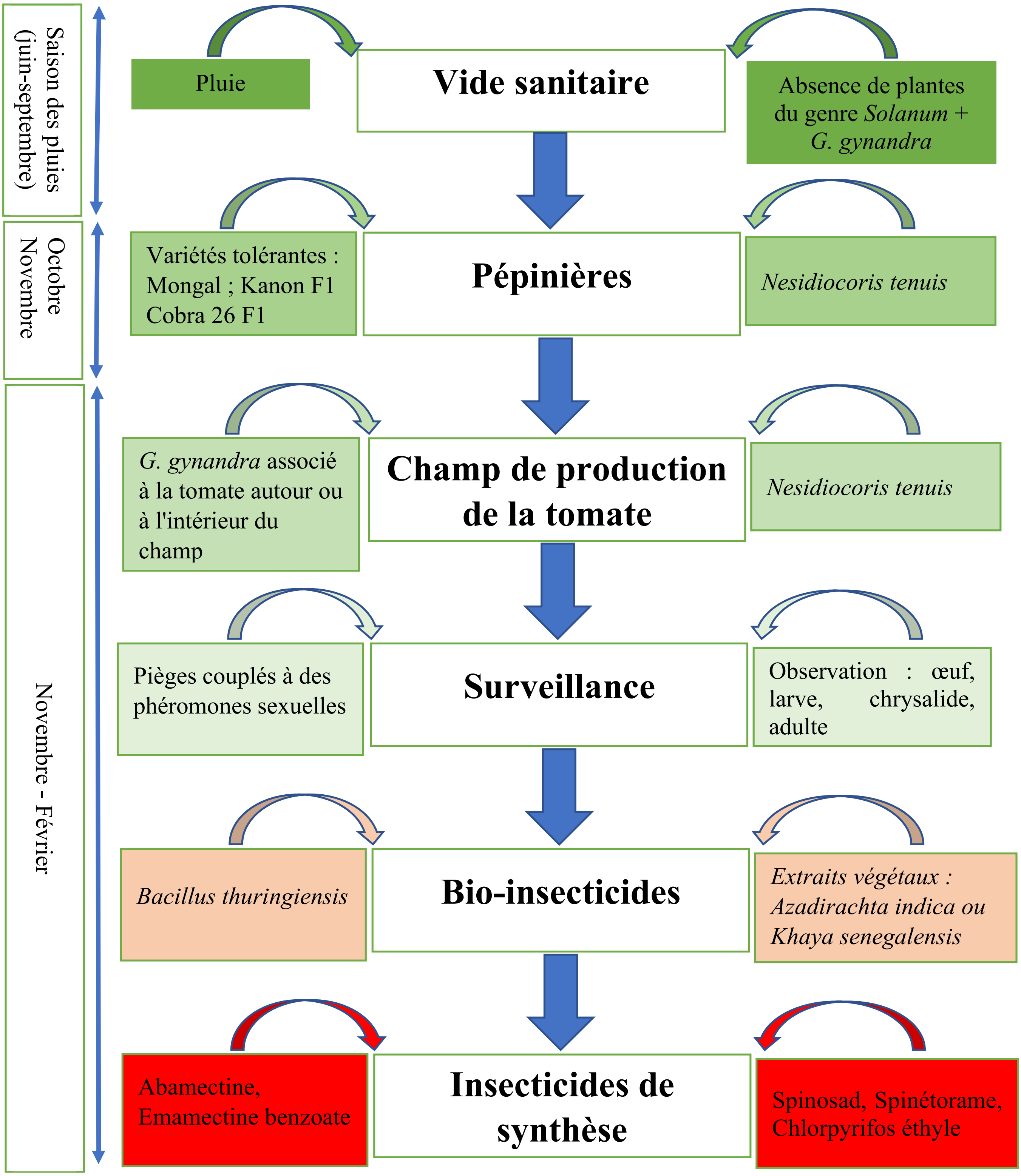


Figure 30 : Itinéraire technique de protection intégrée de tomate produite en saison sèche contre *T. absoluta* au Burkina Faso

2. Conclusion

Le maraîchage a été identifié comme une activité permettant de réduire le chômage des populations, notamment pendant la saison sèche. Parmi les cultures maraîchères, la tomate arrive en deuxième position en termes de contribution économique, avec près de 78,8 milliards de francs CFA gagnés par les acteurs en 2018. Cette filière pourrait contribuer davantage au développement socio-économique et nutritionnel des populations si des solutions étaient trouvées aux ravageurs, notamment *T. absoluta*, qui a envahi le pays en 2016 et qui peut causer des pertes de rendement allant jusqu'à 100%. Ainsi, pour un meilleur développement de cette filière, il est crucial de trouver des solutions pour contenir les ravages de ce déprédateur. Cette thèse a été initiée dans ce sens.

L'objectif est d'améliorer la productivité du secteur de la tomate en réduisant considérablement la prévalence et les dégâts causés par *T. absoluta* grâce à des propositions de stratégies de lutte respectueuses de l'environnement et de la santé des agriculteurs. Ainsi, nous nous sommes d'abord intéressés à l'évaluation de l'impact de l'invasion sur le secteur, puis aux aspects liés à la dynamique et au mode de reproduction de la mineuse, ensuite à la recherche d'une liste positive de pesticides biologiques et de synthèses pour contrer les fortes pressions de la mineuse et enfin aux méthodes préventives basées sur la lutte biologique par l'utilisation de prédateurs, de variétés résistantes et l'identification des plantes hôtes de la mineuse.

L'étude de l'impact de la mineuse sur le secteur de la tomate révèle que le ravageur a conquis tout le pays et provoque des pertes énormes de 45 à 70%, voire 100% chez certains producteurs. Cela a conduit à une augmentation de l'utilisation de pesticides de synthèse, souvent non homologués, ainsi que des conséquences socio-économiques et nutritionnelles désastreuses pour la population.

La saison hivernale serait la meilleure période pour produire des tomates car elle empêcherait le développement de la mineuse. De plus, la saison sèche et froide (octobre à février) serait plus favorable à la production que la saison sèche et chaude (mars-mai) qui représente les plus hauts niveaux de capture de mâles de *T. absoluta*. Malgré l'existence d'une reproduction par parthénogenèse deutérotoque, la forte capacité de capture des mâles suggère que la technique d'annihilation des mâles comme stratégie de lutte pourrait contribuer au contrôle de *T. absoluta* puisque le nombre de descendants de ce ravageur est fonction du nombre d'accouplement des femelles.

Pour contrer les fortes attaques de la mineuse, nous avons pu cribler des biopesticides botaniques et des pesticides chimiques de synthèse. Bien que la plupart des insecticides botaniques nécessitent une augmentation des concentrations recommandées pour être efficaces contre la mineuse des feuilles, certains produits formulés avec des extraits d'*Azadirachta indica*, d'écorce de *Khaya senegalensis* et de *Mitracarpus scaber* se sont révélés efficaces contre les larves de la mineuse des feuilles. Concernant les insecticides de synthèse, une liste positive de produits contenant de l'abamectine, de l'émamectine benzoate, du spinosad, du spinétorame, du chlorpyrifos éthyle et du *Bacillus thuringiensis* a été obtenue.

En ce qui concerne la lutte biologique, nous avons constaté que *N. tenuis*, qui est présent dans tout le pays, pourrait être d'une grande aide dans la mesure où il peut consommer jusqu'à 45 œufs par jour. Cependant, les pesticides à base d'abamectine, d'emamectine benzoate, de spinosad et de spinétorame se sont avérés toxiques contre lui. La découverte de *G. gynandra* comme plante hôte de *N. tenuis*, qui peut l'entretenir et favoriser sa prolifération dans les champs de tomates, est également à signaler.

Parmi les principales variétés de tomates produites dans le pays, nous avons constaté que Mongal, Cobra 26 F1 et Kanon F1 retardaient plus le développement des larves de *T. absoluta* et pouvaient être considérées comme plus tolérantes à la mineuse que les 9 autres variétés utilisées. Quant aux autres espèces cultivées dans le pays, nous avons constaté que seules celles appartenant au genre *Solanum* étaient capables de nourrir *T. absoluta*.

Un vaste programme de vulgarisation des différentes technologies obtenues auprès des vulgarisateurs et des producteurs est nécessaire pour les données les rudiments leur permettant de pouvoir affronter *T. absoluta*.

3 Suggestions et perspectives

A l'issue de ce travail, pour un meilleur développement de la filière tomate, nous pouvons suggérer aux différents acteurs les points suivants :

- ✓ Pour augmenter la résilience des producteurs, l'Etat et les compagnies d'assurance doivent travailler à mettre en place un système d'assurance contre les risques liés aux ravageurs invasifs des cultures ;
- ✓ Afin d'éviter l'effondrement des moyens de subsistance des populations à cause des ravageurs, le système de surveillance phytosanitaire doit être redynamisé, avec un mécanisme d'alerte précoce des nouveaux organismes invasifs ;

- ✓ Le renforcement du contrôle phytosanitaire par les structures habilitées de l'Etat ;
- ✓ L'éradication des traitements pesticides calendaires systématiques et la formation des producteurs au choix de molécules spécifiques, homologuées et à faible rémanence ;
- ✓ La réalisation de formations en cascade, des agents de vulgarisation aux producteurs, par le biais de divers outils (champs-écoles de producteurs, parcelles de démonstration, parcelles vitrines, émissions de radio, posters etc.), sur les bonnes pratiques phytosanitaires basées sur des méthodes de gestions intégrées des nuisibles ;
- ✓ Le renforcement des structures de recherche, notamment dans le domaine de la phytopharmacie et dans l'obtention de nouvelles méthodes alternatives adaptées ;

En termes de perspectives de recherches ultérieures, nous pouvons énumérer :

- ➢ La réalisation de tests terrain sur l'efficacité de la technique d'annihilation des mâles par les phéromones sexuelles ;
- ➢ Le suivi de l'évolution de la résistance des différentes molécules et le renouvellement des listes positives de pesticides si nécessaire ;
- ➢ la recherche d'autres auxiliaires, car nous avons rencontré à plusieurs reprises des Trichogrammes associés à la mineuse ;
- ➢ la poursuite des recherches sur *G gynandra*, notamment sur ses qualités organoleptiques, ses relations sémio-chimiques avec *T. absoluta* et la poursuite des essais au champ en l'associant à la tomate et d'autres solanacées d'importances économiques ;
- ➢ Le criblage variétal pourrait être poursuivi mais cette fois sur des plantes vivantes dans un environnement réel ;
- ➢ L'identification des plantes hôtes, en particulier celles qui ne sont pas cultivées et surtout celles qui sont pérennes.

Références bibliographiques

Références bibliographiques

Abbas, M.S.T., Abuo-Zeid, N.A., Megahed, M.M., 1993. On the natural enemies of the potato tuber moth P*hthorimaea operculella* in Egypt. Egypt. J. Agric. Res. 71, 943–950.

Abbes, K., Chermiti, B., 2014. Propensity of three Tunisian populations of the tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) for deuterotokous parthenogenetic reproduction. African Entomol. 22, 538–544.

Abbes, K., Harbi, A., Chermiti, B., 2012a. Comparative study of 2 protection strategies against *Tuta absoluta* (Meyrick) in late open field tomato crops in Tunisia. EPPO Bull. 42, 297–304.

Abbes, K., Harbi, A., Chermiti, B., 2012b. The tomato leafminer *Tuta absoluta* (Meyrick) in Tunisia: current status and management strategies. EPPO Bull. 42, 226–233.

Abbes, K., Harbi, A., Elimem, M., Hafsi, A., Chermiti, B., 2016. Bioassay of three solanaceous weeds as alternative hosts for the invasive tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) and insights on their carryover potential. African Entomol. 24, 334–342.

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

Abd-Elgawad, M.M.., 2014. Spatial patterns of *Tuta absoluta* and heterorhabditid nematodes. Russ. J. Nematol. 22, 89–100.

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

Abdul-Ridha, M., Alwan, S., Helal, S.., Aziz, K.A., 2012. Alternative hosts of South American tomato moth *Tuta absoluta* (Gelechiidae : Lipedopetra) in Some tomato farms of Najaf province. Euphrates J. of Agriculture Sci. 4, 130–137.

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

Aksoy, E., Kovanci, O.B., 2016. Mass trapping low-density populations of *Tuta absoluta* with various types of traps in field-grown tomatoes. J. Plant Dis. Prot. 123, 51–57.

Alam, S.B., Dib, M.E.A., Djabou, N., Tabti, B., Benyelles, G.N., Costa, J., Muselli, A., 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.

Ali, M., Fathipour, Y., Holst, N., Soufbaf, M., Michaud, J.P., 2019. An egg parasitoid interferes with biological control of tomato leafminer by augmentation of *Nesidiocoris tenuis* (Hemiptera : Miridae). Biol. Control 133, 34–40.

Amiri, A., Bandani, A.R., 2021. Facultative deuterotokous parthenogenesis in *Callosobruchus maculatus*. Zool. Anz. 291, 1–6.

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

Arnó, J., Gabarra, R., 2011. Side effects of selected insecticides on the *Tuta absoluta* (Lepidoptera: Gelechiidae) predators *Macrolophus pygmaeus* and *Nesidiocoris tenuis* (Hemiptera: Miridae). J. Pest Sci. (2004). 84, 513–520.

Awmack, C.S., Leather, S.R., 2002. Host plant quality and fecundity in herbivorous insects. Annu. Rev. Entomol. 47, 817–844.

Azevedo, D., Faria, M.V., Maluf, W.R., Cl, A., Oliveira, B. De, Andr, J., 2003. Zingiberene-mediated resistance to the South American tomato pinworm derived from *Lycopersicon hirsutum* var . hirsutum. Euphytica 134 134, 347–351.

Bacci, L., Marques, É., Cláudio, J., Picanço, M.C., 2019. Seasonal variation in natural mortality factors of *Tuta absoluta* (Lepidoptera : Gelechiidae) in open-field tomato cultivation. J. Appl. Entomol. 143, 21–33.

Badaoui, M.., 2018. Contribution à l'étude de la dynamique des populations de *Tuta absoluta* Meyrick (Lepidoptera ; Gelechiidae) et essais de contrôle biologique sur la culture de tomate ». Thèse de doctorat, Universite Abdelhamid Ibn Badis de Mostaganem, Algerie. 151p.

Badaoui, M.I., Berkani, A., 2011. Morphologie et comparaison des appareils génitaux de deux espèces invasives *Tuta absoluta* Meyrick 1917 et *Phthorimaea operculella* Zeller 1873 (Lepidoptera : Gelechiidae). Entomol. Faun. 63, 191–194.

Bala, I., Mukhtar, M.M., Saka, H.K., Abdullahi, N., Ibrahim, S.S., 2019. Determination of insecticide susceptibility of field populations of tomato leaf miner (*Tuta absoluta*) in northern Nigeria. Agric. Artic. 9, 1–13.

Bambio, Z., 2018. Tomates : une production de 300 000 tonnes par an pour un revenu de 50 milliards de F.CFA. https://www.investirauburkina.net/index.php/item/725-tomates-une-production-de-300-000-tonnes-par-an-pour-un-revenu-de-50-milliards-de-f-cfa. [Accéder le 7 mars 2020].

Barati, R., Hejazi, M.J., Mohammadi, S.A., 2018a. Insecticide susceptibility in *Tuta absoluta* (Lepidoptera: Gelechiidae) and metabolic characterization of resistance to diazinon. J. Econ. Entomol 20, 1–7.

Barati, R., Hejazi, M.J., Mohammadi, S.A., 2018b. Biological and microbial control insecticide susceptibility in *Tuta absoluta* (Lepidoptera : Gelechiidae) and metabolic characterization of resistance to diazinon. J. econ. entomol. 111, 1551–1557.

Barrientos, Z.R., Apablaza, H.J., Norero, S.A., Estay, P.P., 1998. Threshold temperature and thermal constant for the development of the South american tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae). Cienc. e Investig. Agrar. 25, 133–137.

Batalla-carrera, L., Morton, A., Garcıa-del-Pino, F., 2010. Efficacy of entomopathogenic nematodes against the tomato leafminer *Tuta absoluta* in laboratory and greenhouse conditions. BioControl 55, 523–530.

Bawin, T., Backer, L. De, Dujeu, D., Legrand, P., Megido, R.C., Francis, F., Verheggen, F.J., 2014. Infestation level influences oviposition site selection in the tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae). Insects 5, 877–884.

Bawin, T., Collard, F., Backer, L. De, Barthélémy, B., Compère, P., Francis, F., Verheggen, J., 2017. Structure and distribution of the sensilla on the antennae of *Tuta absoluta* (Lepidoptera : Gelechiidae). Micron 96, 16–28.

Bawin, T., Dujeu, D., De Backer, L., Fauconnier, M.-L., Lognay, G., Delaplace, P., Francis, F., Verheggen, F.J., 2015. Could alternative solanaceous hosts act as refuges for the tomato leafminer, *Tuta absoluta*? Arthropod. Plant. Interact. 9, 425–435.

Bawin, T., Dujeu, D., De Backer, L., Francis, F., Verheggen, F.J., 2016. Ability of *Tuta absoluta* (Lepidoptera: Gelechiidae) to develop on alternative host plant species. Can. Entomol. 148, 434–442.

Baxter, S.W., Badenes-Pérez, F.R., Morrison, A., Vogel, H., Crickmore, N., Kain, W., Wang, P., Heckel, D.G., Jiggins, C.D., 2011. Parallel evolution of *Bacillus thuringiensis* toxin resistance in Lepidoptera. Genetics, 189, 675–679.

Berger, M., Puinean, A.M., Randall, E., Zimmer, C.T., Silva, W.M., Bielza, P., Field, L.M., Hughes, D., Mellor, I., Hassani-Pak, K., Siqueira, H.A.A., Williamson, M.S., Bass, C., 2016. Insecticide resistance mediated by an exon skipping event. Mol. Ecol. 25, 5692–5704.

Biondi, A., Desneux, N., Amiens-Desneux, E., Siscaro, G., Zappalà, L., 2013. Biology and developmental strategies of the palaearctic parasitoid *Bracon nigricans* (Hymenoptera: Braconidae) on the neotropical moth *Tuta absoluta* (Lepidoptera: Gelechiidae). J. Econ. Entomol. 106, 1638–1647.

Biondi, A., Guedes, R.N.C., Wan, F., Desneux, N., 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.

Biondi, A., Zappalà, L., Di Mauro, A., Tropea Garzia, G., Russo, A., Desneux, N., Siscaro, G., 2016. Can alternative host plant and prey affect phytophagy and biological control by the zoophytophagous mirid *Nesidiocoris tenuis*? BioControl 61, 79–90.

Blanca, J., Cañizares, J., Cordero, L., Pascual, L., Diez, M.J., Nuez, F., 2012. Variation revealed by SNP genotyping and morphology provides insight into the origin of the tomato. PLoS One e48198, 7, 1-17

Blazhevski, S., Kalaitzaki, A.P., Tsagkarakis, A.E., 2018. Impact of nitrogen and potassium fertilization regimes on the biology of the tomato leaf miner *Tuta absoluta* 37, 157–174.

Bleeker, P.M., Mirabella, R., Diergaarde, P.J., Vandoorn, A., Tissier, A., Kant, M.R., 2012. Improved herbivore resistance in cultivated tomato with the sesquiterpene biosynthetic pathway from a wild relative. PNAS 109, 20124–20129.

Boggs, C.L., 1992. Resource allocation: exploring connections between foraging and life history. Funct. Ecol. 6, 508–518.

Bouagga, S., Urbaneja, A., Pérez-Hedo, M., 2018. Combined use of predatory mirids with *Amblyseius swirskii* (Acari: Phytoseiidae) to enhance pest management in sweet pepper. J. Econ. Entomol. 111, 1112–1120.

Brévault, T., Sylla, S., Diatte, M., Bernadas, G., Diarra, K., 2014. *Tuta absoluta* Meyrick (Lepidoptera : Gelechiidae): A new threat to tomato production in Sub-Saharan Africa. African Entomol. 22, 441–444.

Caballero-Mendieta, N., Cordero, C., 2013. Male mating costs in a butterfly that produces small ejaculates. Physiol. Entomol. 38, 318–325.

Cabello, T., J.R., Gallego, E., Vila, A., Soler, M., del Pino, A., Carnero, A., E., Hernandez Suarez, Polaszek., A., 2009. Biological control of the South American tomato pinworm, *Tuta absoluta* (Lep.: Gelechiidae), with releases of *Trichogramma achaeae* (Hym.: Trichogrammatidae) in tomato greenhouses of Spain. IOBCWPRS Bull 49, 225–230.

CABI, 2020. Crop protection compendium. Wallingford, UK: CAB International. https://www.cabi.org/cpc/ [accessed on 1 November 2020].

Cagnotti, C.L., Arias, A.E., Ermantraut, E.N., Andorno, A. V, Viscarret, M.M., Lopez, S.N., 2020. Life history study of the mirid *Tupiocoris cucurbitaceus* feeding on *Tuta absoluta* eggs : implications for biological control and its combination with inherited sterility. BioControl, 66, 207–216.

Calvo, F.J., Soriano, J.D., Stansly, P.A., Belda, J.E., 2016. Can the parasitoid *Necremnus tutae* (Hymenoptera: Eulophidae) improve existing biological control of the tomato leafminer *Tuta aboluta* (Lepidoptera: Gelechiidae)? Bull. Entomol. Res. 106, 502–511.

Calvo, J., Bolckmans, K., Stansly, P.A., Urbaneja, A., 2009. Predation by *Nesidiocoris tenuis* on *Bemisia tabaci* and injury to tomato. BioControl 54, 237–246.

Campolo, O., Cherif, A., Ricupero, M., Siscaro, G., Grissa-Lebdi, K., Russo, A., Cucci, L.M., Di Pietro, P., Satriano, C., Desneux, N., Biondi, A., Zappalà, L., Palmeri, V., 2017. Citrus peel essential oil nanoformulations to control the tomato borer, *Tuta absoluta*: Chemical properties and biological activity. Sci. Rep. 7, 1–10.

Campos, M.R., Amiens-Desneux, E., Béarez, P., Soares, M.A., Ponti, L., Biondi, A., Harwood, J.D., Desneux, N., 2021. Impact of low temperature and host plant on *Tuta absoluta* . Entomol. Exp. Appl. 1–13.

Campos, M.R., Rodrigues, A.R.S., Silva, W.M., Silva, T.B.M., Silva, R.F., Guedes, R.N.C., Siqueira, H.A.A., 2014. Spinosad and the Tomato Borer *Tuta absoluta* : A bioinsecticide, an invasive pest threat , and high insecticide resistance. PLoS One e103235, 9, 1-12

Campos, M.R., Silva, T.B.M., Silva, W.M., Silva, J.E., Siqueira, H.A.A., 2015a. Spinosyn resistance in the tomato borer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). J. Pest Sci. 88, 405–412.

Campos, M.R., Silva, T.B.M., Silva, W.M., Silva, J.E., Siqueira, H.A.A., 2015b. Susceptibility of *Tuta absoluta* (Lepidoptera : Gelechiidae) Brazilian populations to ryanodine receptor modulators. Pest Manag. Sci. 71, 537–544.

Caparros Megido, R., Backer, L. De, Ettaib, R., Brostaux, Y., Fauconnier, M.-L., Delaplace, P., Lognay, G., Belkadhi, M.S., Haubruge, E., Francis, F., Verheggen, F.J., 2014. Role of larval host plant experience and solanaceous plant volatile emissions in *Tuta absoluta* (Lepidoptera : Gelechiidae) host finding behavior. Arthropod-Plant Interact. 8, 293–304.

Caparros Megido, Rudy, BROSTAUX, Y., Haubruge, E., Verheggen, F.J., 2013a. Propensity of the tomato leafminer, *Tuta absoluta* (Lepidoptera : Gelechiidae), to develop on four potato plant varieties. Am. J. Potato Res. 90, 255– 260.

Caparros Megido, R., Haubruge, E., Verheggen, F.J., 2012. First evidence of deuterotokous parthenogenesis in the tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). J. Pest Sci. 85, 409–412.

Caparros Megido, Rudy, Haubruge, E., Verheggen, F.J., 2013b. Pheromone-based management strategies to control the tomato leafminer, *Tuta absoluta* (Lepidoptera : Gelechiidae). A review. Biotechnol. Agron. Soc. Environ. 17, 475–482.

CAPES, 2007. Contribution des cultures de saison sèche à la réduction de la pauvreté et à l'amélioration de la sécurité alimentaire. Ouagadougou: Burkina Faso. 120 p. https://www.capes.bf/IMG/pdf/cultures_de_saison_seche.pdf.

Carvalho, G.A., Corrêa, S.A., de Oliveria, L.O., Chediak, M., Siqueira, H.A.A., Guedes, R.N.C., 2018. *Wolbachia* strains, and lack of genetic diversity and parthenogenesis in Brazilian populations of *Tuta absoluta* (Lepidoptera: Gelechiidae). J. Appl. Entomol. 1–6.

Castresana, J., Puhl, L., 2017. Comparative study among a variety of solar-powered LED traps to capture tomato leafminers *Tuta absoluta* adults by mass trapping in tomato greenhouses in the Province of Entre Ríos, Argentina. Idesia 35, 1–11.

CEDEAO, UEMOA, CILSS, CILSS, 2016. Catalogue Régional des Espèces et Variétés

Végétales CEDEAO-UEMOA-CILSS ,Tomate, 96-99

http://www.insah.org/doc/pdf/Catalogue_Regional_semences_vf_janv_2017.pdf,

[Access on 22 March 2021].

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

Chailleux, A., Bearez, P., Pizzol, J., Amiens-Desneux, E., Ramirez-Romero, R., Desneux, N., 2013a. Potential for combined use of parasitoids and generalist predators for biological control of the key invasive tomato pest *Tuta absoluta*. J. Pest Sci. 86, 533–541.

Chailleux, A., Biondi, A., Han, P., Tabone, E., 2013b. Suitability of the pest – plant system *Tuta absoluta* (Lepidoptera : Gelechiidae)– tomato for Trichogramma (Hymenoptera : Trichogrammatidae) parasitoids and insights for biological control. J. Econ. Entomol. 106, 2310–2321.

Chailleux, A., Desneux, N., Seguret, J., Khanh, H.D.T., Maignet, P., Tabone, E., 2012.

Assessing European egg parasitoids as a mean of controlling the invasive South American Tomato Pinworm *Tuta absoluta.* PLOS ONE e48068 7, 1-8.

Chegini, S.G., Abbasipour, H., 2017. Chemical composition and insecticidal effects of the essential oil of cardamom, *Elettaria cardamomum* on the tomato leaf miner, *Tuta absoluta*. Toxin Rev. 36, 12–17.

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

Cherif, A., Attia-Barhoumi, S., Mansour, R., Zappalà, L., Grissa-Lebdi, K., 2019. Elucidating key biological parameters of *Tuta absoluta* on different host plants and under various temperature and relative humidity regimes. Entomol. Gen. 39, 1–17.

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

Cherif, A., Mansour, R., Grissa-lebdi, K., 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., Verheggen, F., 2019. A review of *Tuta absoluta* (Lepidoptera : Gelechiidae) host plants and their impact on management strategies. Biotechnol. Agron. Soc. Environ. 23, 270–278.

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

Chermiti, B., Abbes, K., 2012. Comparison of pheromone lures used in mass trapping to control the tomato leafminer *Tuta absoluta* (Meyrick, 1917) in industrial tomato crops in Kairouan (Tunisia). EPPO Bull. 42, 241–248.

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

Chweya, J.A., Mnzava, N.A., 1997. Cat's whiskers *Cleome gynandra* L. Promoting the conservation and use of underutilized and neglected crops. 11. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy.

Clark, J.M., Scott, J.G., Campos, F., Bloomquist, J.R., 1995. Resistance to avermectins: extent, mechanisms, and management implications. Annu. Rev. Entomol. 40, 1–30.

Cocco, A., Deliperi, S., Delrio, G., 2013. Control of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in greenhouse tomato crops using the mating disruption technique. J. Appl. Entomol. 137, 16–28.

Cocco, A., Deliperi, S., Lentini, A., Mannu, R., Delrio, G., 2015. Seasonal phenology of *Tuta absoluta* (Lepidoptera: Gelechiidae) in protected and open-field crops under Mediterranean climatic conditions. Phytoparasitica 43, 713–724.

Coelho, M.C.F., França, F.H., 1987. Biologia, quetotaxia da larva e descriçao da pupa e adulto da traça do tomateiro. Pesqui. Agropecuária Bras. 22, 129–135.

Contreras, J., Mendoza, J.E., Martinez-Aguirre, M.R., Garcia-Vidal, L., Izquierdo, J., Bielza, P., 2014. Efficacy of enthomopathogenic fungus *Metarhizium anisopliae* against *Tuta absoluta* (Lepidoptera : Gelechiidae). J. Econ. Entomol. 107, 121–124.

Crespo-Pérez, V., Régnière, J., Chuine, I., Rebaudo, F., Dangles, O., 2014. Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes. Glob. Chang. Biol. 21, 82–96.

CSP, 2019. Liste globale des pesticides autorisés par le Comité Sahélien des Pesticides Version de Novembre 2019. Institut du Sahel, Bamako, Mali 45p. https://www.csan-niger.com/wp-content/uploads/2020/06/liste-globale- pesticides-autotises-csp-nov-2019.pdf

Cuthbertson, A.G.S., Mathers, J.J., Blackburn, L.F., Korycinska, A., Luo, W., Jacobson, R.J., Northing, P., 2013. Population development of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under simulated UK glasshouse conditions. Insects 4, 185–197.

Dader, B., Colomer, I., Adan, A., Medina, P., Vinuela, E., 2019. Compatibility of early natural enemy introductions in commercial pepper and tomato greenhouses with repeated pesticide applications. Insect Sci. 27, 1111–1124.

Dammak, M., Khedher, B.S., Boukedi, H., Chaib, I., Laarif, A., Tounsi, S., 2015. Involvement of the processing step in the susceptibility / tolerance of two lepidopteran larvae to *Bacillus thuringiensis* Cry1Aa toxin. Pestic. Biochem. Physiol. 127, 46–50.

Davies, T.G.E., Williamson, M., 2009. Interactions of pyrethroids with the voltage-gated sodium channel interactions of pyrethroids with the voltage-gated sodium channel. Bayer CropScience Journal, *62*, 159–178.

de Brito, E.F., Baldin, E.L.L., Silva, R. de C.M., Ribeiro, L. do P., Vendramim, J.D., 2015. Bioactivity of piper extracts on *Tuta absoluta* (Lepidoptera: Gelechiidae) in tomato. Pesqui. Agropecu. Bras. 50, 196–202.

de Medeiros, M.A., Sujii, E.R., Morais, H.C. De, 2010. Mortality factors at egg stage of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on organic tomato system and on conventional tomato system. Bragantia, Campinas 70, 72–80.

Dehliz, A., Lakhdari, W., Acheuk, F., Aoudjit, R., 2017. *Euphorbia guyoniana* aqueous extract efficiency against tomato leaf miner in southern East Algeria. Org. Agr. 8, 349–354.

Desneux, N., Luna, M.G., Guillemaud, T., Urbaneja, A., 2011. The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond : The new threat to tomato world production. J. Pest Sci. (2004). 84, 403–408.

Desneux, N., Wajnberg, E., Wyckhuys, K.A.G., Burgio, G., Arpaia, S., Narváez-Vasquez, C. A., González-Cabrera, J., Ruescas, D.C., Tabone, E., Frandon, J., Pizzol, J., Poncet, C., Cabello, T., Urbaneja, A., 2010. Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. J. Pest Sci. (2004). 83, 197–215.

Dhanapal, R., Singh, R.N., Raghuraman, M., Mohan, M., 2021. Evaluation of predatory potential and prey stage preference of mirid bug , *Nesidiocoris tenuis* on tomato pinworm, *Tuta absoluta*. Biologia (Bratisl).

Doumbia, M., Yoboue, K., Kra, D.K., Klimaszewski, J., Kwadjo, K.E., Douan, B.G., Dagnogo, M., 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.

Douris, V., Papapostolou, K.M., Ilias, A., Roditakis, E., Kounadi, S., Riga, M., Nauen, R., Vontas, J., 2017. Investigation of the contribution of RyR target-site mutations in diamide resistance by CRISPR/Cas9 genome modification in Drosophila. Insect Biochem. Mol. Biol. 87, 127–135.

Ebadah, I.M., Shalaby, S.E.M., Moawad, S.S., 2016. Impact of certain natural plant oils and chemical insecticides against tomato insect pests. J. Entomol. 13, 84–90.

Ekesi, S., Adamu, R.S., Maniania, N.K., 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.

El-Aassar, M.R., Soliman, M.H.A., Abd Elaal, A.A., 2015. Efficiency of sex pheromone traps and some bio and chemical insecticides against tomato borer larvae, *Tuta absoluta*

(Meyrick) and estimate the damages of leaves and fruit tomato plant. Ann. Agric. Sci. 60, 153–156.

EPPO, 2007. Distribution Maps of Quarantine Pests for Europe: *Tuta absoluta.* European and Mediterranean Plant Protection Organisation. Consulté 19/09/2019 [Http://www.appo.org/quarantine/insects/Tuta_abso luta/DSGNORAB_Map.htm:1-2].

EPPO, 2005. Data sheets on quarantine pests : *Tuta absoluta*. EPPO Bull. 35, 434–435.

Erb, M., Meldau, S., Howe, G.A., 2012. Role of phytohormones in insect-specific plant reactions. Trends Plant Sci. 17, 250–259.

Estay, P., 2000. Polilla del tomate *Tuta absoluta* (Meyrick). Inf. INIA La Platina 9, 2–5.

FAOSTAT, 2021. Crops and livestock products. Food Agric. Organ. United Nations (FAO), Stat. Div. Rome Italy. http//www.fao.org/faostat/en/#data/QCL (accessed 18 août 2021).

Fernández, M., Amor, F., Bengochea, P., Velázquez, E., Medina, P., Fereres, A., Viñuela, E., 2012. Effects of the insecticides methoxyfenozide and abamectin to adults of the whiteflynatural enemies *Eretmocerus mundus* Mercet (Hymenoptera: Aphelinidae), *Orius laevigatus* Fieber (Hemiptera: Anthocoridae) and *Nesidiocoris tenuis* Reuter (Hemiptera: Miridae). Pestic. Benef. Org. IOBC-WPRS. Bull. 82, 1–7.

Fernandez, S., Montagne., A., 1990. Preferencia de oviposicion de las hembras y duracion, crecimiento y sobrevivencia de las larvas de *Scrobipalpula absoluta* (Meyrick) en diferentes Solanaceas. Bol. Entomol. Venez N. S. 5, 100–106.

Fernández, S., Montagne, A., 1989. Biologia del minador del tomate, *Scrobipalpula absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Boletín Entomol. Venez. (NS). 5, 88–89.

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

Ferracini, C., Ingegno, B.L., Navone, P., Ferrari, E., Mosti, M., Tavella, L., Alma, A., Ferracini, C., Ingegno, B.L., Navone, P., Ferrari, E., Mosti, M., Tavella, L., Alma, A., 2012. Adaptation of indigenous larval parasitoids to *Tuta absoluta* (Lepidoptera : Gelechiidae) in Italy. J. Econ. Entomol. 105, 1311–1319.

Finney, D.., 1964. Probit Analysis. Cambridge University Press, Cambridge, UK.

Fournier, D., 2005. Mutations of acetylcholinesterase which confer insecticide resistance in insect populations. Chem. Biol. Interact. 158, 257–261.

Fragoso, D.F.M., Túler, A.C., Pratissoli, D., Carvalho, J.R., Valbon, W.R., Queiroz, V.T. D., Pinheiro, P.F., Costa, A. V., Bueno, R.C.O.F., 2021. Biological activity of plant extracts on the small tomato borer *Neoleucinodes elegantalis*, an important pest in the Neotropical region. Crop Prot. 145, 2.

Garba, M., Streito, J.C., Gauthier, N., 2020. First report of three predatory bugs (Heteroptera: Miridae) in tomato fields infested by the invasive South American tomato pinworm, *Tuta absoluta* in Niger: an opportunity for biological control? Phytoparasitica 48, 215–229.

García, M.., Espul, J.., 1982. Bioecology of the tomato moth (*Scrobipalpula absoluta*) in Mendoza , Argentine Republic . Rev. Investig. Agropecu. 17, 135-146.

Gavkare, O., Sharma, P.L., 2017. Influence of temperature on development of *Nesidiocoris tenuis* (Reuiter) preying on trialeurodes vaporariorum (WESTWOOD) on Tomato. Entomol. News 127, 230–241.

Genç, H., 2016. The tomato leafminer , *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae): pupal key characters for sexing individuals. Turkish J. Zool. 40, 801–805.

Germain, J.F., Lacordaire, A.-I., Cocquempot, C., Ramel, J.M., Oudard, E., 2009. Un nouveau ravageur de la tomate en France: *Tuta absoluta*. PHM-REVUE Hortic. 512, 37–41.

Gharekhani, G., Salek-Ebrahimi, H., 2014a. Life Table Parameters of *Tuta absoluta*

(Lepidoptera : Gelechiidae) on different varieties of tomato. J. Econ. Entomol. 107, 1765–1770.

Gharekhani, G., Salek-Ebrahimi, H., 2014b. Evaluating the damage of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on some cultivars of tomato under greenhouse condition. Arch. Phytopathol. Plant Prot. 47, 429–436.

Giustolin, T.A., Vendramim, J.D., Alves, S.B., Vieira, S.A., Pereira2, R.M., 2001. Susceptibility of *Tuta absoluta* (Meyrick) (Lep ., Gelechiidae) reared on two species of Lycopersicon to *Bacillus thuringiensis* var . kurstaki. J. Appl. Ent. 125, 551–556.

Goda, N.., El-Heneidy, A.H., Djelouah, K., Hassan, N., 2015. Integrated pest management of the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in tomato fields in Egypt. Egypt J Biol Pest Control. 25, 655–661.

Gonçalves, L.D., Maluf, W.R., Cardoso, M. das G., Resende, J.T.V. de, Castro, E.M. de, Santos, N.M., Nascimento, I.R. do, Faria, V.M., 2006. Relationship between zingiberene, foliar trichomes and repellence of tomato plant to *Tetranychus evansi*. Pesq. agropec. bras., Brasília 41, 267–273.

Gontijo, P.C., Picanço, M.C., Pereira, E.J.G., Martins, J.C., Chediak, M., Guedes, R.N.C., 2012. Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta*. Ann. Appl. Biol. 162, 50–59.

González-Cabrera, J., Mollá, O., Montón, H., Urbaneja, A., 2011. Efficacy of *Bacillus thuringiensis* (Berliner) in controlling the tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). BioControl 56, 71–80.

Grant, C., Jacobson, R., Bass, C., 2021. Parthenogenesis in UK field populations of the tomato leaf miner, *Tuta absoluta* , exposed to the mating disruptor Isonet T. Pest Manag. Sci. 77, 3445–3449.

Grant, C., Jacobson, R., Ilias, A., Berger, M., Vasakis, E., Bielza, P., Zimmer, C.T., Williamson, M.S., Richard, H., Vontas, J., Roditakis, E., Bass, C., 2019. The evolution of multiple-insecticide resistance in UK populations of tomato leafminer , *Tuta absoluta*. Pest Manag Sci 2019; 75, 2079–2085.

Gripenberg, S., Mayhew, P.J., Parnell, M., Roslin, T., 2010. Review and synthesis a meta-analysis of preference – performance relationships in phytophagous insects. Ecol. Lett. 13, 383–393.

Grissa-Lebdi, K., Skander, M., Mhafdhi, M., Belhadj, R., 2011. Lutte intégrée contre la mineuse de la tomate, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) en Tunisie. Faun. Entomol. 63, 125–132.

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

Guedes, R.N.C., Picanço, M.C., 2012. The tomato borer *Tuta absoluta* in South America: Pest status, management and insecticide resistance. EPPO Bull. 42, 211–216.

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

Guedes, R.N.C., Siqueira, H.A.A., 2012. The tomato borer *Tuta absoluta* : insecticide resistance and control failure. CAB Rev. 7, 1–7.

Guevara, E.J., Porcel, M., Calixto, A.M., Bueno, V.D.P., Jr, A.M., 2020. Interactions between the nematode *Heterorhabditis amazonensis* JPM4 and the predator *Macrolophus basicornis* : Two natural enemies of *Tuta absoluta* native to South America. Neotrop Entomol 49, 108–115.

Guillemaud, T., Blin, A., Goff, I. Le, Desneux, N., Reyes, M., Tabone, E., Tsagkarakou, A., Nino, L., Lombaert, E., 2015. The tomato borer, *Tuta absoluta*, invading the Mediterranean Basin, originates from a single introduction from Central Chile. Sci. Rep. 14, 1–5.

Guo, L., Liang, P., Zhou, X., Gao, X., 2014. Novel mutations and mutation combinations of ryanodine receptor in a chlorantraniliprole resistant population of *Plutella xylostella* (L.) 1–7.

Haddi, K., Berger, M., Bielza, P., Cifuentes, D., Field, L.M., Gorman, K., Rapisarda, C., Williamson, M.S., Bass, C., 2012. Identification of mutations associated with pyrethroid resistance in the voltage-gated sodium channel of the tomato leaf miner (*Tuta absoluta*). Insect Biochem. Mol. Biol. 42, 506–513.

Haddi, K., Berger, M., Bielza, P., Rapisarda, C., Williamson, M.S., Moores, G., Bass, C., 2017. Mutation in the ace-1 gene of the tomato leaf miner (*Tuta absoluta*) associated with organophosphates resistance. J. Appl. Entomol. 141, 612–619.

Han, P., Bayram, Y., Shaltiel, L., Sohrabi, F., Saji, A., Tair, U., 2019a. *Tuta absoluta* continues to disperse in Asia : damage , ongoing management and future challenges. J. Pest Sci. (2004). 92, 1317–1327.

Han, P., Desneux, N., Becker, C., Larbat, R., Le Bot, J., Adamowicz, S., Zhang, J., Lavoir, A.-V., 2019b. 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., Desneux, N., Michel, T., Le Bot, J., Seassau, A., Wajnberg, E., Amiens-Desneux, E., Lavoir, A.V., 2016. Does plant cultivar difference modify the bottom-up effects of resource limitation on plant-insect herbivore interactions? J. Chem. Ecol. 42, 1293–1303.

Han, P., Lavoir, A.V., Le Bot, J., Amiens-Desneux, E., Desneux, N., 2014. Nitrogen and water availability to tomato plants triggers bottom-up effects on the leafminer *Tuta absoluta*. Sci. Rep. 4, 1–8.

Hasan, F., Ansari, M.S., 2011. Effects of different brassicaceous host plants on the fitness of *Pieris brassicae* (L .). Crop Prot. 30, 854–862.

Hashemitassuji, A., Safaralizadeh, M.H., Aramideh, S., Hashemitassuji, Z., 2015. Effects of *Bacillus thuringiensis* var. kurstaki and Spinosad on three larval stages 1st, 2nd and 3rd of tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in laboratory conditions. Arch. Phytopathol. Plant Prot. 48, 377–384.

Heuzé, V., Tran, G., Lebas, F., 2020. African spiderflower (*Gynandropsis gynandra*). Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO.

Hilker, M., Meiners, T., 2011. Plants and insect eggs : How do they affect each other ? Phytochemistry 72, 1612–1623.

Idriss, G.E.A., Du Plessis, H., Khamis, F.M., Ekesi, S., Tanga, C.M., Mohamed, S.A., 2020. Host range and effects of plant species on preference and fitness of *Tuta absoluta* (Lepidoptera: Gelechiidae). J. Econ. Entomol. 113, 1279–1289.

IRAC, 2011. *Tuta absoluta* - -The Tomato Leafminer or Tomato Borer. www.irac-online.org

IRAC, 2018. IRAC - 2018 - IRAC Mode of Action Classification Scheme. www.irac-online.org

IRAC, 2020. IRAC Mode of Action Classification Scheme. Insectic. Resist. Action Comm. 1–30. www.irac-online.org

Isman, M.B., 2006. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu. Rev. Entomol. 51, 45–66.

Jactel, H., Verheggen, F., Thiéry, D., Escobar-gutiérrez, A.J., Gachet, E., Desneux, N., Group, W., Delorme, R., Frérot, B., Jean, A., Mironet, V., 2019. Alternatives to neonicotinoids 129, 423–429.

Jallow, M.F.., Dahab, A., Albaho, M., Devi, V., 2018a. Efficacy of some biorational insecticides against *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) under laboratory and greenhouse conditions in Kuwait. J Appl Entomol. 1–9.

Jallow, M.F.., Dahab, A.A., Albaho, M.S., Devi, V.Y., Awadh, D.G., Thomas, B.M., 2018b. Baseline susceptibility and assessment of resistance risk to flubendiamide and chlorantraniliprole in *Tuta absoluta* (Lepidoptera : Gelechiidae) populations from Kuwait. Appl. Entomol. Zool. 54, 91–99.

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

Jamoussi, K., Sellami, S., Nasfi, Z., Krichen-makni, S., Tounsi, S., 2013. Efficiency and midgut histopathological effect of the newly isolated *Bacillus thuringiensis* KS δ-Endotoxins on the emergent pest *Tuta absoluta.* J. Microbiol. Biotechnol 23, 1099–1106.

Jiang, D., Du, Y., Nomura, Y., Wang, X., Wu, Y., Zhorov, B.S., Dong, K., 2015. Mutations in the transmembrane helix S6 of domain IV confer cockroach sodium channel resistance to sodium channel blocker insecticides and local anesthetics. Insect Biochem. Mol. Biol. 66, 88–95.

Kamali, S., Karimi, J., Koppenhofer, M.A., 2017. Biological and microbial control new insight into the management of the tomato leaf miner , *Tuta absoluta* (Lepidoptera : Gelechiidae) with entomopathogenic nematodes. Biol. Microb. Control 111, 112–119.

Khambay, B., Farnham, A., Beddie, D., 1994. Relationships between pyrethroid structure and level of resistance in houseflies (*Musca domestica* L.). Briggs C.G., ed. Adv. Chem. Insect Control III. R. Soc. Chem. Cambridge 117–126.

Khederi, S.J., Khanjani, M., Hosseini, M.A., LEITE, G.L.D., JAFARI, M., 2014. Role of different trichome style in the resistance of *Lycopersicon hirsutum* genotypes to *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae). Ecol. Montenegrina 1, 55–63.

Khidr, A.A., Gaffar, S.A., Nada, M.S., Taman, A.A., Salem, F.A., 2013. New approaches for controlling tomato leafminer , *Tuta absoluta* (Meyrick) in tomato fields in egypt. Egypt. J. Agric. Res., 91, 335–348.

Kiliç, T., 2010. First record of *Tuta absoluta* in Turkey. Phytoparasitica 38, 243–244.

Kim, J.G., Lee, W.H., Yu, Y.M., Yasunaga-Aoki, C., Jung, S.H., 2016. Lifecycle, biology, and descriptions of greenhouse biological control agent, *Nesidiocoris tenuis* (Reuter, 1895) (Hemiptera: Miridae). J. Fac. Agric. Kyushu Univ. 61, 313–318.

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

Kim, S.Y., Ahn, H.G., Ha, P.J., Lim, U.T., Lee, J.-H., 2018. Toxicities of 26 pesticides against 10 biological control species. J. Asia. Pac. Entomol. 21, 1–8.

Kimba, A., Abdoulaye, A.K., Delmas, P., Assoumane, B.D., Haougui, A., 2014. Les semences de tomate disponibles au Niger 2014, 1–17.

Klieber, J., Reineke, A., 2016. The entomopathogen *Beauveria bassiana* has epiphytic and endophytic activity against the tomato leaf miner *Tuta absoluta*. J. Appl. Entomol. 140, 580–589.

Konus, M., 2014. Analysing resistance of different *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) strains to abamectin insecticide. Turkish J. Biochem. 39, 291–297.

Koppel, A.A.L., Herbert, D.A., Kuhar, T.P., Malone, S., 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.

Koudjil, M., Boukabcha, F., Harichane, H., 2015. Perte en rendement et déprédation par la mineuse , *Tuta absoluta* (Lepidoptera , Gelechiidae) sur la culture de tomate , dans la wilaya de Chlef (Algérie). Nat. Technol. B-Sciences Agron. Biol. 12, 73–85.

Krechemer, F.S., Foerster, L.A., 2017. Development, reproduction, survival, and demographic patterns of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on Different Commercial tomato cultivars. Neotrop. Entomol. 46, 694–700.

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

Leckie, B.M., Halitschke, R., De Jong, D.M., Smeda, J.R., Kessler, A., Mutschler, M.A., 2014. Quantitative trait loci regulating the fatty acid profile of acylsugars in tomato. Mol Breed. 716, 1201–1213.

Lee, M.S., Albajes, R., Eizaguirre, M., 2014. Mating behaviour of female *Tuta absoluta* (Lepidoptera : Gelechiidae): polyandry increases reproductive output mating behaviour of female *Tuta absoluta* (Lepidoptera : Gelechiidae): polyandry increases reproductive output. J. Pest Sci. 87, 429–439.

Leite, G.L.D., Picanço, M., Guedes, R.N.C., Zanuncio, J.C., 2000. Role of plant age in the resistance of *Lycopersicon hirsutum* f . glabratum to the tomato leafminer *Tuta absoluta* (Lepidoptera : Gelechiidae). Sci. Hortic. (Amsterdam). 89, 103–113.

Lenteren, J.C. Van, Bueno, V.H.P., Burgio, G., Lanzoni, A., Montes, F.C., Silva, D.B., Jong, P.W. De, Hemerik, L., 2019. Pest kill rate as aggregate evaluation criterion to rank biological control agents : a case study with Neotropical predators of *Tuta absoluta* on tomato 812–820.

Lietti, M.M.M., Botto, E., Alzogaray, R.A., 2005. Insecticide resistance in Argentine populations of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Neotrop. Entomol. 34, 113–119.

Lima, I.P., Faria, M. V, Filho, R.B.L., Lavras, U.F. De, Cedeteg, C., 2015. Indirect selection of industrial tomato genotypes rich in zingiberene and resistant to *Tuta absoluta* Meyrick. Genet. Mol. Res. 14, 15081–15089.

Lobos, E., Occhionero, M., Werenitzky, D., Fernandez, J., Gonzalez, L.M., Rodriguez, C., Calvo, C., Lopez, G., OEhlschlager, A.C., 2013. Optimization of a trap for *Tuta absoluta* Meyrick (Lepidoptera : Gelechiidae) and trials to determine the effectiveness of mass trapping. Neotrop Entomol 42, 448–457.

MAAH, 2017. Situation de référence du programme de développement des cultures fruitières et légumières (PDCFL), Phase 2018-2022, Ministère de l'Agriculture et des Aménagements Hydrauliques. Ouagadougou, Burkina Faso, 61 p.

MAAH, 2019. Rapport de l'Enquête maraichère 2018, Ministere de l'agriculture, et des Amenagements Hydro-Agricoles. Ouagadougou, Burkina Faso, 58p.

MAAH, 2020. Annuaire des statistiques agricoles 2018, Ministere de l'agriculture, et des Amenagements Hydro-Agricoles. Ouagadougou, Burkina Faso, 290p.

MAH, 2011. Rapport général du module maraîchage. Ministère de l'Agriculture et de l'Hydraulique. Ouagadougou : Burkina Faso, 318 p. http://cns.bf/IMG/pdf/rga_maraichage_derniere_version.pdf

MAHRH, 2007. Rapport national sur l'état des ressources phytogénétiques pour l'alimentation et l'agriculture. Ministere de l'Agriculture de l'Hydraulique et des Ressources Halieutiques. Ouagadougou : Burkina Faso, 45p.

Mano, E., Kambou, G., Yaro, B., F, K., Somda, I., 2019. Phytochemical composition and biological efficiency of *Cleome viscosa* L . leaves , *Parkia biglobosa* (Jacq.) Br . Ex G . Don pods powders extracts against *Helicoverpa armigera* (Hübner) (Lepidoptera : Noctuidae) of tomato. Int. J. Agric. Pol. Res. 7, 10–16.

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

Mansour, R., Brévault, T., Chailleux, A., Cherif, A., Grissa-Lebdi, K., Haddi, K., Mohamed, S.A., Nofemela, R.S., Oke, A., Sylla, S., Tonnang, H.E.Z., Zappalà, L., Kenis, M., Desneux, N., Biondi, A., 2018. Occurrence, biology, natural enemies and management of *Tuta absoluta* in Africa, Entomologia Generalis. 38, 83-112.

Marouelli, W.A., Gravina, C.S., Michereff, M., 2013. Sprinkler and drip irrigation in the organic tomato for single crops and when intercropped with coriander. Rev. Ciência Agronômica 44, 825–833.

Martinou, A.F., Seraphides, N., Stavrinides, M.C., 2014. Lethal and behavioral effects of pesticides on the insect predator *Macrolophus pygmaeus*. Chemosphere 96, 167–173.

Mccaskill, D., Croteau, R., 1999. Strategies for bioengineering the development and metabolism of glandular tissues in plants. Nat. Biotechnol. 17, 31–36.

Meabeb, H.A.., Rizk, A.M., El Hefnawy, N.., Agamy, E.., 2015. Effects and economics of different treatments against the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera : Gelichiidae) at Harvesting time. Egypt. J. Biolocal Pest Control 25, 167–170.

Menken, S.B.J., Wiebosch-Steeman, M., 1988. Clonal diversity, population structure, and dispersal in the parthenogenetic moth *Ectoedemia argyropeza*. Entomol. Exp. Appl. 49, 141–152.

Mercier, B., Prost, J., Prost, M., 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.

Michaelides, G., Seraphides, N., Pitsillou, M., Sfenthourakis, S., 2019. Susceptibility of Cypriot *Tuta absoluta* populations to four targeted insecticides and control failure likelihood. J Appl Entomol. 143, 508–517.

Michaelides, G., Sfenthourakis, S., Pitsillou, M., Seraphides, N., 2017. Functional response and multiple predator effects of two generalist predators preying on *Tuta absoluta* eggs. Pest Manag. Sci. 74, 332–339.

Michereff-Filho, M., Vilela, E.F., Jham, G.N., Attygalle, A., Svatoš, A., Meinwald, J., 2000. Initial studies of mating disruption of the tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae) using synthetic sex pheromone. J. Braz. Chem. Soc. 11, 621–628.

MINEFIDE, 2016. Plan National de Développement Economique et Social (PNDES): synthèse. Ouagadougou : Burkina Faso, 20p.

Miranda, M.M.M., Picanço, M., Zanuncio, J.C., Guedes, R.N.C., 1998. Ecological life table of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Biocontrol Sci. Technol. 8, 597–606.

Mirhosseini, A.M., Fathipour, Y., Holst, N., Soufbaf, M., Michaudd, J.P., 2019. An egg parasitoid interferes with biological control of tomato leafminer by augmentation of *Nesidiocoris tenuis* (Hemiptera: Miridae). Biol. Control 133, 34–40.

Mirhosseini, M.A., Fathipour, Y., Soufbaf, M., Reddy, G.V.P., 2020. Implications of using two natural enemies of *Tuta absoluta* (Lepidoptera : Gelechiidae) toward tomato yield enhancement leaf. Bull. Entomol. Res. 109. 617–625.

Mobki, M., Safavi, S.A., Safaralizadeh, M.H., Panahi, O., 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.

Mohamed, E.S.I., Mahmoud, M.E.E., Elhaj, M.A.M., Mohamed, S.A., Ekesi, S., 2015. Host plants record for tomato leaf miner *Tuta absoluta* (Meyrick) in Sudan. EPPO Bull. 45, 108–111.

Mollá, O., Biondi, A., Alonso-Valiente, M., Urbaneja, A., 2014. A comparative life history study of two mirid bugs preying on *Tuta absoluta* and *Ephestia kuehniella* eggs on tomato crops: Implications for biological control. BioControl 59, 175–183.

Mollá, O., González-Cabrera, J., Urbaneja, A., 2011. The combined use of *Bacillus* *thuringiensis* and *Nesidiocoris tenuis* against the tomato borer *Tuta absoluta*. BioControl 56, 883–891.

Moore, J.E., 1983. Control of tomato leafminer (*Scrobipalpula absoluta*) in Bolivia. Trop. Pest Manag. 29, 231–238.

Moradi, S., Khani, S., Ansari, M., Shahlaei, M., 2019. Atomistic details on the mechanism of organophosphates resistance in insects : Insights from homology modeling , docking and molecular dynamic simulation. J. Mol. Liq. 276, 59–66.

Mori, B.A., Evenden, M.L., 2013. Factors affecting pheromone-baited trap capture of male coleophora deauratella, an invasive pest of clover in Canada. J. Econ. Entomol. 106, 844–854.

Mouttet, R., Kaplan, I., Bearez, P., Amiens, E., Nicolas, D., 2013. Spatiotemporal patterns of induced resistance and susceptibility linking diverse plant parasites. Oecologia 173, 1379–1386.

MRSI, 2014. Catalogue national des espèces et variétés agricoles du Burkina Faso. 81p. http://www.doc-developpement-durable.org/file/Agriculture/catalogues-de-semences/ catalogue-national-des-especes-et-varietesagricoles-du-burkina-faso_2014.pdf

Murovhi, J., Phophi, M.M., Mafongoya, P., 2020. Efficacy of plant materials in controlling Aphids on okra (*Abelmoschus esculentus* L. Moench) in Limpopo Province of South Africa. Agronomy 10, 1-11.

Naika, S., Jeude, J. van L. de, Goffau, M. de, Hilmi, M., Dam, B. van, 2005. La culture de la tomate. 105p.

Nannini, M., Atzori, F., Murgia, G., Pisci, R., Sanna, F., 2012. Use of predatory mirids for control of the tomato borer *Tuta absoluta* (Meyrick) in Sardinian greenhouse tomatoes. EPPO Bull. 42, 255–259.

Nannini, M., Foddi, F., Murgia, G., Pisci, R., Sanna, F., 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.

Naselli, M., Urbaneja, A., Siscaro, G., Jaques, J.A., Zappalà, L., Flors, V., Pérez-Hedo, M., 2016a. Stage-related defense response induction in tomato plants by *Nesidiocoris tenuis.* Int. J. Mol. Sci. 17.

Naselli, M., Zappalà, L., Gugliuzzo, A., Tropea Garzia, G., Biondi, A., Rapisarda, C., Cincotta, F., Condurso, C., Verzera, A., Siscaro, G., 2016b. Olfactory response of the zoophytophagous mirid *Nesidiocoris tenuis* to tomato and alternative host plants. Arthropod. Plant. Interact. 11, 121–131.

Nault, B.A., Shelton, A.M., Gangloff-kaufmann, J.L., Clark, M.E., Werren, J.L., Rosa, J.C.C., Kennedy, G.G., 2006. Reproductive modes in onion Thrips (Thysanoptera : Thripidae) populations from New York onion fields. Environ. Entomol. 35, 1264–1271.

Ndereyimana, A., Nyalala, S., Murerwa, P., Gaidashova, S., 2019a. Potential of entomopathogenic nematode isolates from Rwanda to control the tomato leaf miner , *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) Egypt. J. Biol. Pest Control. 29, 1-7.

Ndereyimana, A., Nyalala, S., Murerwa, P., Gaidashova, S., 2019b. Pathogenicity of some commercial formulations of entomopathogenic fungi on the tomato leaf miner , *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae). Egypt. J. Biol. Pest Control 29, 1–5.

Negi, S., Sharma, P.L., Sharma, K.C., Verma, S.C., 2018. Effect of host plants on developmental and population parameters of invasive leafminer , *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae). Phytoparasitica 46, 213–221.

NTS, 2020. Jampakt (F1 hybrid determinate salad tomato) http://www.natseeds.co.zw/nts/products-and-service.

Onyango, C.M., Kunyanga, C.N., Ontita, E.G., Narla, R.D., Kimenju, J.W., 2013. Production , utilisation and indigenous knowledge of spider plant in Kenya. African Crop Sci. Conf. Proc. 11, 925–930.

Osman, M.A.M., Agriculture, F., 2015. Evaluation of two protective strategies for controlling the tomato leaf miner *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) in Egypt 25, 113–120.

Ouardi, K., Chouibani, M., Rahel, M.A., El Akel, M., 2012. Stratégie nationale de lutte contre la mineuse de la tomate *Tuta absoluta* Meyrick. EPPO Bull. 42, 281–290.

Ouedraogo, M., 1995. Histoire et conséquences de l'introduction du maraîchage en zone soudano-sahélienne au Burkina Faso. Chauveau Jean-Pierre (ed.), Yung J.M. Montpellier, 257–263.

Oztemiz, S., Kutuk, H., Portakaldali, M., 2012. Biological control of tomato leaf miner (Lepidoptera: Gelechiidae) on greenhouse-grown tomato in Turkey. J. Entomol. Sci. 47, 272–274.

Paladino, L.Z.C., Ferrari, M.E., Lauría, J.P., Cagnotti, C.L., Šíchová, J., López, S.N., 2016. The effect of X-Rays on cytological traits of *Tuta absoluta* (Lepidoptera: Gelechiidae). Florida Entomol. 99, 43–53.

PDCA, 2019. Plan de gestion des pestes (PGP). Programme de Développement et de Compétitivité Agricole. Ouagadougou : Burkina Faso, 139p. http://documents.worldbank.org/curated/en/582031553748055393/pdf/Plan-de-Gestion-des-Pestes.pdf

Peralta, I.E., Spooner, D., 2007. Peralta I. E., Spooner D., 2007. History, origin and early cultivation of tomato (Solanaceae). Genetic improvement of Solanaceous crops. Enfield (NH). Sci. Publ. 2, 1–24.

Perdikis, D., Arvaniti, K., 2016. Nymphal development on plant vs. leaf with and without prey for two omnivorous predators: *Nesidiocoris tenuis* (Reuter, 1895) (Hemiptera: Miridae) and *Dicyphus errans* (Wolff, 1804) (Hemiptera: Miridae). Entomol. Gen. 35, 297–306.

Pereyra, P.C., Sanchez, E.N., 2006. Effect of two Solanaceous plants on developmental and population parameters of the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae). Neotrop. Entomol. 35, 671–676.

Perez-Hedo, M., Alonso-Valiente, M., Vacas, S., Gallego, C., Rambla, J.., Navarro-Llopis, V., Granell, A., Urbaneja, A., 2021. Eliciting tomato plant defenses by exposure to herbivore induced plant volatiles. Entomol. Gen. 41, 209–218.

Pérez-Hedo, M., Urbaneja-Bernat, P., Jaques, J.A., Flors, V., Urbaneja, A., 2015. Defensive plant responses induced by *Nesidiocoris tenuis* (Hemiptera: Miridae) on tomato plants. J. Pest Sci. 88, 543–554.

Pfeiffer, D.., Muniappan, R., Sall, D., Diatta, P., Diongue, A., Dieng, E.., 2013. First record of *Tuta absoluta* (Lepidoptera : Gelechiidae) in Senegal. Florida Entomol. 96, 661–662.

Pires, L.M., Marques, E.J., Oliveira, J.V. DE, Alves, S.B., 2010. Seleção de ısolados de fungos entomopatogênicos para o controle de *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) e sua compatibilidade com alguns ınseticidas usados na cultura do tomateiro. Neotrop. Entomol. 39, 977–984.

Pires, L.M., Marques, E.J., Wanderley-Teixeira, V., Teixeira, Á.A.C., Alves, L.C., Alves, E.S.B., 2009. Ultrastructure of *Tuta absoluta* parasitized eggs and the reproductive potential of females after parasitism by *Metarhizium anisopliae*. Micron 40, 255–261.

Polat, B., 2019. Efficacy of mass trapping of tomato leafminer (*Tuta absoluta*) with different types and colours of traps in open- field tomato. Appl. Ecol. Environ. Res. 17, 15721–15730.

Portakaldali, M., Öztemiz, S., Kütük, H., 2013. A new host plant for *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Turkey. J. Entomol. Res. Soc. 15, 21–24.

Pouey, G.F., Chirinos, D.T., Rivero, G., 1994. Notas sobre *Keiferia lycopersicella* (Walsingham), (Lepidoptera: Gelechiidae), en Venezuela. Boletín Entomol. Venez. 9, 203–206.

Povolný, D., 1994. Gnorimoschemini of southern South America VI: Identification keys, checklist of Neotropical taxa and general considerations (Insecta, Lepidoptera, Gelechiidae). Steenstrupia 20, 1–42.

Proffit, M., Birgersson, G., Bengtsson, M., Jr., R.R., Witzgall, P., Lima, E., 2011. Attraction and oviposition of *Tuta absoluta* females in response to tomato leaf volatiles. J Chem Ecol 37, 565–574.

Ramdani, C., Bouharroud, R., Sbaghi, M., Mesfioui, A., El Bouhssini, M., 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.

Ranc, N., 2010. Analyse du polymorphisme de gènes de composantes de la qualité des fruits dans les sources génétiques sauvages et cultivées de tomate ; recherche d'association gènes/ QTL. Montpellier, SupAgro. Thèse de doctorat : 348p

Razuri, V., Vargas, E., 1975. Biologie et comportement de *Scrobipalpula absoluta* Meyrick (Lep ., Gelechiidae) sur tomates . Rev. Peru. Entomol. 18, 84–89.

Resende, J.T. V, Maluf, W.R., Cardoso, M. das G., Nelson, D.L., Faria, M.V., 2002. Inheritance of acylsugar contents in tomatoes derived from an interspecific cross with the wild tomato *Lycopersicon pennellii* and their effect on spider mite repellence. Genet. Mol. Res. 1, 106–116.

Reyes, M., Rocha, K., Alarcón, L., Siegwart, M., Sauphanor, B., 2012. Metabolic mechanisms involved in the resistance of field populations of *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) to spinosad. Pestic. Biochem. Physiol. 102, 45–50.

Roditakis, E., Mavridis, K., Riga, M., Vasakis, E., Morou, E., Rison, L., Vontas, J., 2017a. Identification and detection of indoxacarb resistance mutations in the para sodium channel of the tomato leafminer , *Tuta absoluta*. Pest Manag Sci 73, 1679–1688.

Roditakis, E., Skarmoutsou, C., Staurakaki, M., 2013a. Toxicity of insecticides to populations of tomato borer *Tuta absoluta* (Meyrick) from Greece. Pest Manag Sci 69, 834–840.

Roditakis, E., Skarmoutsou, C., Staurakaki, M., del Rosario Martínez-Aguirre, M., García-Vidal, L., Bielza, P., Haddi, K., Rapisarda, C., Rison, J.L., Bassi, A., Teixeira, L. a., 2013b. Determination of baseline susceptibility of European populations of *Tuta absoluta* (Meyrick) to indoxacarb and chlorantraniliprole using a novel dip bioassay method. Pest Manag. Sci. 69, 217–227.

Roditakis, E., Stavrakaki, M., Ilias, A., Ioannidis, P., Vontas, J., 2021. Investigating resistance to emamectin benzoate in the tomato borer *Tuta Absoluta* key points : Res. Sq. 1–24.

Roditakis, E., Steinbach, D., Moritz, G., Vasakis, E., Stavrakaki, M., Ilias, A., García-Vidal, L., Martínez-Aguirre, M. del R., Bielza, P., Morou, E., Silva, J.E., Silva, W.M., Siqueira, H.A.A., Iqbal, S., Troczka, B.J., Williamson, M.S., Bass, C., Tsagkarakou, A., Vontas, J., Nauen, R., 2017b. Ryanodine receptor point mutations confer diamide insecticide resistance in tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae). Insect Biochem. Mol. Biol. 80, 11–20.

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

Roditakis, E., Vasakis, E., Grispou, M., Stavrakaki, M., Nauen, R., Gravouil, M., Bassi, A., 2015. First report of *Tuta absoluta* resistance to diamide insecticides. J. Pest Sci. 88, 9–16.

Rodríguez S., M., Gerding P., M., France I., A., 2006. Selección de aislamientos de hongos entomopatógenos para el control de huevos de la polilla del tomate, *Tuta absoluta* Meyrick (Lepidoptera: gelechiidae). Agric. Tec. 66, 151–158.

Rouamba, A., Belem, J., Tarpaga, W. V., Otoidobiga, L., Ouedraogo, L., Konaté, Y.A., Kambou, G., 2013. Itineraires techniques de production des tomates d'hivernage FBT. Fiche tecnique 4p.

Rwomushana, I., Beale, T., Chipabika, G., Day, R., Gonzalez-Moreno, P., Lamontagne-Godwin, J., Makale, F., Pratt, C., Tambo, J., 2019. Evidence note. tomato leafminer (*Tuta absoluta*): impacts and coping strategies for Africa.. CABI Working Paper 12, 56p.

Sabry, A. kazafy H., Metwallya, H.M., Abolmaatyb, S.M., 2016. Compatibility and efficacy of entomopathogenic nematode, *Steinernema carpocapsae* all alone and in combination with some insecticides against *Tuta absoluta*. Der Pharm. Lett. 8, 311–315.

Salazar, E.R., Araya, J.E., 2001. Tomato moth, *Tuta absoluta* (Meyrick) response to insecticides in Arica, Chile. Agric. Téc. 61, 429–435.

Salem, S.A., Abdel-Moniem, A.S.H., 2015. Evaluation of non-traditional approaches for controlling tomato moth, *Tuta absoluta* Meyrick (Lepidoptera, Gelechiidae), a new invasive pest in Egypt. Arch. Phytopathol. Plant Prot. 48, 319–326.

Sanchez, J.A., Lacasa, A., Arnó, J., Castañé, C., Alomar, O., 2009. Life history parameters for *Nesidiocoris tenuis* (Reuter) (Het., Miridae) under different temperature regimes. J. Appl. Entomol. 133, 125–132.

Sannino, L., Espinosa, B., 2010. *Tuta absoluta*, guide to knowledge and recent acquisitions for a suitable control. Informatore Agrar. 46, 1–113.

Santana, P.A., Kumar, L., Da Silva, R.S., Picanço, M.C., 2019. Global geographic distribution of *Tuta absoluta* as affected by climate change. J. Pest Sci. 92, 1373–1385.

Sawadogo, M.W., Somda, I., Nacro, S., Legrève, A., Verheggen, F., 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., Somda, I., Nacro, S., Legrève, A., Verheggen, F.J., 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.

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

Sellami, S., Cherif, M., Abdelkefi-mesrati, L., 2014. Toxicity , activation process , and histopathological effect of *Bacillus thuringiensis* vegetative insecticidal protein Vip3Aa16 on *Tuta absoluta*. Appl Biochem Biotechnol. 175, 1992-1999.

Seth, R.K., Kaur, J.J., Rao, D.K., Reynolds, S.E., 2002. Sperm transfer during mating, movement of sperm in the female reproductive tract, and sperm precedence in the common cutworm Spodoptera litura. Physiol. Entomol. 27, 1–14.

Silva, G.A., Picanço, M.C., Bacci, L., Crespo, A.L.B., Rosado, J.F., Guedes, R.N.C., 2011. Control failure likelihood and spatial dependence of insecticide resistance in the tomato pinworm, *Tuta absoluta*. Pest Manag. Sci. 67, 913–920.

Silva, J.E., Assis, C.P.O., Ribeiro, L.M.S., Siqueira, H.A.A., 2016. Field-evolved resistance and cross-resistance of Brazilian *Tuta absoluta* (Lepidoptera: Gelechiidae) populations to diamide insecticides. J. Econ. Entomol. 109, 2190–2195.

Silva, J.E., Ribeiro, L.M. da S., Vinasco, N., Narciso, R., Narciso, G.R., Siqueira, H.Á.A., 2019. Field - evolved resistance to chlorantraniliprole in the tomato pinworm *Tuta absoluta* : inheritance , cross - resistance profile , and metabolism. J. Pest Sci. (2004). 92, 1421–1431.

Silva, S.S., 2008. Reproductive biology factors influencing the behavioral management of *Tuta* *absoluta* (Meyrick) (Lepidoptera : Gelechiidae). MS thesis: Universidade Federal Rural de Pernambuco

Silva, T.B.M., Silva, W.M., Campos, M.R., Silva, J.E., Ribeiro, L.M.S., Siqueira, H.A.A., 2016. Susceptibility levels of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) to minor classes of insecticides in Brazil. Crop Prot. 79, 80–86.

Silva, W.M., Berger, M., Bass, C., Balbino, V.Q., Amaral, M.H.P., Campos, M.R., Siqueira, H.A.A., 2015. Status of pyrethroid resistance and mechanisms in Brazilian populations of *Tuta absoluta*. Pestic. Biochem. Physiol. 122, 8–14.

Silva, W.M., Berger, M., Bass, C., Williamson, M., Moura, D.M.N., Ribeiro, L.M.S., Siqueira, H.A.A., 2016. Mutation (G275E) of the nicotinic acetylcholine receptor α6 subunit is associated with high levels of resistance to spinosyns in *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Pestic. Biochem. Physiol. 131, 1–8.

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

Siqueira, H., Guedes, R., Fragoso, D., Magalhaes, L., 2001. Abamectin resistance and synergism in Brazilian populations of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Int. J. Pest Manag. 47, 247–251.

Siqueira, H.A.A., Guedes, R.N.C., Picanc, M.C., 2000a. Cartap resistance and synergism in populations of *Tuta absoluta* (Lep., Gelechiidae). J. Appl. Entomol. 124, 233–238.

Siqueira, H.A.A., Guedes, R.N.C., Picanço, M.C., 2000b. Insecticide resistance in populations of *Tuta absoluta* (Lepidoptera: Gelechiidae). Agric. For. Entomol. 2, 147–153.

Soares, M.A., Campos, M.R., Passos, L.C., Carvalho, G.A., Haro, M.M., Lavoir, A.-V., Biondi, A., Zappalà, L., Desneux, N., 2019. Botanical insecticide and natural enemies: a potential combination for pest management against *Tuta absoluta*. J. Pest Sci. (2004). 92, 1433–1443.

Soderlund, M., Bloomquist, J., 1989. Neurotoxic actions of pyrethroid insecticides. Ann. Rev. Entomol. 34, 77–96.

Sohrabi, F., Nooryazdan, H., Gharati, B., 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.

Some, K., Kabore, K.B., Bassirou, B., Barry, M., 2014. Catalogue national des especes et varietes agricoles.

Son, D., 2018. Analyse des risques liés à l'emploi des pesticides et mesure de la performance de la lutte intégrée en culture de tomate au Burkina Faso, THèse de Doctorat en sciences agronomique et ingenierie biologique.

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

Son, D., Somda, I., Legreve, A., Schiffers, B., 2017b. Pratiques phytosanitaires des producteurs de tomates du Burkina Faso et risques pour la santé et l ' environnement. Cah. Agric. 26, 6.

Son, D., Yarou, B.B., Bayendi, S.M.L., Verheggen, F., Francis, F., Legrève, A., Somda, I., 2018. Détermination par piégeage de la diversité et de l ' abondance des familles d ' insectes associées à la culture de tomate (*Solanum lycopersicum* L.) au Burkina Faso. Entomol. Faun. 71, 1–15.

Souza, J.C. DE, Reis, P.R., 1986. Chemical control of tomato moti-4 in minas gerais, Brazil. Pesq. agropec. bras, Brasflha 21, 343–354.

Spooner, D.., Anderson, G.., Jansen, R.., 1993. Chloroplast DNA evidence for the interrelationships of tomatoes, potatoes, and pepinos (Solanaceae). Am. J. Bot. 80, 676–688.

Suinaga, F.A., Picanço, M., Jham, G.N., Brommonschenkel, S.H., 1999. Causas Químicas de Resistência de *Lycopersicon peruvianum* L. a *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae). An. Soc. Entomol. Bras. 28, 313–321.

Suomalainen, E., Saura, A., Lokki, J., 1976. Evolution of parthenogenetic insects. Evol. Biol. 209–257.

Sylla, S., Brévault, T., Bal, A.B., Chailleux, A., Diatte, M., Desneux, N., Diarra, K., 2017. Rapid spread of the tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae), an invasive pest in Sub-Saharan Africa. Entomol. Gen. 36, 269–283.

Sylla, S., Brévault, T., Monticelli, L.S., Diarra, K., Desneux, N., 2019. Geographic variation of host preference by the invasive tomato leaf miner *Tuta absoluta*: implications for host range expansion. J. Pest Sci. (2004). 92, 1387–1396.

Sylla, S., Seydi, O., Diarra, K., Brévault, T., 2018. Seasonal decline of the tomato leafminer , *Tuta absoluta* , in the shifting landscape of a vegetable-growing area. Entomol. Exp. Appl. 166, 638–647.

Taadaouit, N.A.I.T., Nilahyane, A., Hsaine, M., Rochdi, A., Hormatallah, A., Bouharroud, R., 2011. L'effet des extraits végétaux sur la mineuse de la tomate *Tuta absoluta* (Lepidoptera, Gelechiidae). Actes du Premier Congrès International de l'Arganier, Agadir. 90, 411–417.

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

Technisem, 2016. Catálogo technisem 2016 https://issuu.com/mozasem/docs/cat__logo_technisem.

Thiombiano, A.S., 2020. 5^{e} Recensement Général de la Population et de l'Habitation (RGPH) : Près de 20,5 millions d'habitants dont 51,7 % de femmes au Burkina Faso. https://theworldnews.net/bf-news/5e-rgph-pres-de-20-5-millions-d-habitants-dont-51-7-de-femmes-au-burkina-faso

Thompson, G.D., Dutton, R., Sparks, T.C., 2000. Spinosad – a case study : an example from a natural products discovery programme. Pest Manag Sci 56, 696–702.

Tonnang, H.E.Z., Mohamed, S.F., Khamis, F., Ekesi, S., 2015. Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: Implications for phytosanitary measures and management. PLoS One 10, 1–19.

Torres-vila, L.M., Rodr, M.C., Lacasa-plasencia, A., Bielza-lino, P., Rodr, Á., 2002. Pyrethroid resistance of *Helicoverpa armigera* in Spain : current status and agroecological perspective. Agric Ecosyst Environ. 93, 55–66.

Troczka, B., Zimmer, C.T., Elias, J., Schorn, C., Bass, C., Davies, T.G.E., Field, L.M., Williamson, M.S., Slater, R., Nauen, R., 2012. Resistance to diamide insecticides in diamondback moth, *Plutella xylostella* (Lepidoptera : Plutellidae) is associated with a mutation in the membrane-spanning domain of the ryanodine receptor. Insect Biochem. Mol. Biol. 42, 873–880.

Tropea Garzia, G., Siscaro, G., Biondi, A., Zappalà, L., 2012. *Tuta absoluta*, a South American pest of tomato now in the EPPO region: Biology, distribution and damage. EPPO Bull. 42, 205–210.

Uchoa-Fernandes, M., Della Lucia, T., Vilela, E., 1995. Mating, oviposition and pupation ofScrobipalpuloides absoluta (Meyr.) (Lepidoptera: Gelechiidae). An. Soc. Entomol. Bras. 24, 159–164.

Ugurlu Karaagac, S., 2012. The current status of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiiidae) in Turkey and baseline toxicity of some insecticides. EPPO Bull. 42, 333–

336.

Ugurlu Karaağaç, S., 2015. Enzyme activities and analysis of susceptibility levels in Turkish *Tuta absoluta* Populations to chlorantraniliprole and metaflumizone insecticides. Phytoparasitica 43, 693–700.

Ullé, J.A., Nakano, O., 1994. Avaliação do dano de *Scrobipalpuloides absoluta* (Meyrick) (Lepidoptera:Gelechiidae) em plantas de tomateiro com diferentes níveis de infestação. An. da Soc. Entomol. do Bras. 23, 155–162.

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

Urbaneja-Bernat, P., Bru, P., González-Cabrera, J., Urbaneja, A., Tena, A., 2019. Reduced phytophagy in sugar - provisioned mirids. J. Pest Sci. 92, 1139–1148.

Urbaneja, A., González-Cabrera, J., Arnó, J., Gabarra, R., 2012. Prospects for the biological control of *Tuta absoluta* in tomatoes of the Mediterranean basin. Pest Manag. Sci. 68, 1215–1222.

Urbaneja, A., Montón, H., Mollá, O., 2008. Suitability of the tomato borer *Tuta absoluta* as prey for *Macrolophus pygmaeus* and *Nesidiocoris tenuis*. J. Appl. Entomol. 133, 292–296.

Urbaneja, A., Vercher, R., Navarro, V., Marí, G.F., Porcuna, L.J., 2007. La polilla del tomate, "*Tuta absoluta*." Phytoma España 194, 16–24.

USDA-APHIS, 2011. Federal import quarantine order for host materials of tomato leafminer, *Tuta absoluta* (Meyrick). Washington, DC United States Dep. Agric. 1–6.

USDA-APHIS, 2014. Federal order for U.S. Imports of host materials of tomato leaf miner (*Tuta absoluta*). Washington, DC United States Dep. Agric. 1–6.

Vacas, S., Alfaro, C., Primo, J., Navarro-llopis, V., 2011. Studies on the development of a mating disruption system to control the tomato leafminer, *Tuta absoluta* Povolny (Lepidoptera : Gelechiidae) 1473–1480.

Vais, H., Williamson, M.S., Devonshire, A.L., Usherwood, P.N.R., 2001. The molecular interactions of pyrethroid insecticides with insect and mammalian sodium channels. Pest Manag Sci 57, 877–888.

Van Damme, M. V, Beck, B.K., Berckmoes, E., Moerkens, R., Wittemans, L., Vis, D.R., Nuyttens, D., Casteels, F.H., Maes, M., Tirry, L., Clercq, D.P., 2015. Efficacy of entomopathogenic nematodes against larvae of *Tuta absoluta* in the laboratory. Pest Manag Sci. 72, 1702-1709.

Vargas, C., 1970. Observations on the bionomics and natural enemies of the tomato moth, *Gnorimoschema absoluta* (Meyrick) (Lep . Gelechiidae). Idesia 47, 75–110.

Verheggen, F., Fontus, R.B., 2019. First record of *Tuta absoluta* in Haïti. Entomol. Gen. 38, 349–353.

Visintin, T., Galdino, D.S., Picanço, M.C., Gomes, E., De Morais, F., Rodrigues Silva, N., Aelton, G., Da Silva, R., Lopes, M.C., 2011. Bioassay method for toxicity studies of insecticide formulations to *Tuta absoluta* (Meyrick, 1917). Ciênc. agrotec., Lavras 35, 869–877.

Wakisaka, S., Tsukuda, R., Nakasuji, F., 1991. Life tables of the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Yponomeutidae) and effects of rainfall, temperature and host plants on survival and reproduction. Japanese J. Appl. Entomol. Zool. 35, 115–122.

Wakisaka, S., Tsukuda, R., Nakasuji, F., 1992. Effects of natural enemies, rainfall, temperature and host plants on survival and reproduction of the diamondback moth and other crucifer pests. In: Talekar, N.S. (Ed.), Diamondback Moth and Other Crucifer Pests: Proceedings of the Second International Wo 16–36.

WeatherSpark.com, 2020. rapports détaillés sur les conditions météorologiques typiques des localités du Burkina Faso. https://fr.weatherspark.com/y/40160/M%C3%A9t%C3%A9o-habituelle-%C3%A0-Ouagadougou-Burkina-Faso. [Accéder le 7 mars 2020].

Witzgall, P., Kirsch, P., Cork, A., 2010. Sex pheromones and their impact on pest management. J Chem Ecol. 36, 80–100.

Woods, H.A., 2010. Water loss and gas exchange by eggs of *Manduca sexta* : Trading off costs and benefits. J. Insect Physiol. 56, 480–487.

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

Yano, E., Nakauchi, M., Watanabe, T., Watanabe, H., 2019. Life history traits of *Nesidiocoris tenuis* on *Bemisia tabaci* and *Thrips palmi*. BioControl. 65:155–164.

Yarou, B.B., Bawin, T., Boullis, A., Heukin, S., Lognay, G., Verheggen, F.J., Francis, F., 2017. Oviposition deterrent activity of basil plants and their essentials oils against *Tuta absoluta* (Lepidoptera: Gelechiidae). Environ. Sci. Pollut. Res. 1–9.

Zalom, F., Burrack, H., Bingham, R., Price, R., Ferguson, L., 2008. Olive fruit fly (*Bactrocera oleae*) introduction and establishment in California. Acta Hortic. 791, 619–627.

Zappalà, L., Biondi, Antonio, Alma, A., Al-Jboory, I.J., Arno, J., Bayram, A., Chailleux, A., El-Arnaouty, A., Gerling, D., Liora, S.-H., Guenaoui, Y., Siscaro, G., Stavrinides, M., Tavella, L., Aznar, R.V., Urbaneja, A., Desneux, N., 2013. Natural enemies of the South American moth , *Tuta absoluta*, in Europe, North Africa and Middle East , and their potential use in pest control strategies. J Pest Sci. 86, 635–647.

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

Zekeya, N., Mtambo, M., Ramasamy, S., Chacha, M., Ndakidemi, P.A., Mbega, E.R., 2019. First record of an entomopathogenic fungus of tomato leafminer , *Tuta absoluta* (Meyrick) in Tanzania. Biocontrol Sci. Technol. 29, 626–637.

Zhang, G.-F., Liu, W.-X., Guo, J.-Y., Zhang, Y.-B., Wan, F.-H., 2013. Species-specific COI primers for rapid identification of *Tuta absoluta* (Meyrick), a significant, potential alien species. J. Biosaf. 22, 80–85.

Zhang, G. fen, Ma, D. ying, Wang, Y. sheng, Gao, Y. hua, Liu, W. xue, Zhang, R., Fu, W. jun, Xian, X. qing, Wang, J., Kuang, M., Wan, F. hao, 2020. First report of the South American tomato leafminer, *Tuta absoluta* (Meyrick), in China. J. Integr. Agric. 19, 1912–1917.

Zibaee, I., Mahmood, K., Esmaeily, M., Bandani, A.R., Kristensen, M., 2018. Organophosphate and pyrethroid resistances in the tomato leaf miner *Tuta absoluta* (Lepidoptera: Gelechiidae) from Iran. J. Appl. Entomol. 142, 181–191.

Annexe

1. Liste des articles

- Sawadogo, W.M., Somda, I., Nacro, S., Legrève, A. & Verheggen, F. 2020. Cinq années d'invasion : Impact de *Tuta absoluta* (Meyrick) sur la production de tomate au Burkina Faso. **Tropicultura** 38, 1–14. https://doi.org/10.25518/2295-8010.1638
- Sawadogo W. M., Somda I., Nacro S., Legrève A.L. & Verheggen F. J., 2020, Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso. **Physiological Entomology** 45 (4): 147-153. https://doi.org/10.1111/phen.12332
- Savadogo, A., Bakouan, B. B., Sawadogo, M. W., Nébié, K., Dabiré, R., Son, D., Somda, I., Bonzi, S., Dabiré, G., Kambiré, H., Legrève, A., Verheggen, F. J., & Nacro, S. (2020). Distribution et dégâts associés au thrips de l'oignon, Thrips tabaci L. (Thysanoptera : Thripidae) en fonction de la zone agro-climatique au Burkina Faso. International Journal of Biological and Chemical Sciences, 14(6), 2037–2048. https://doi.org/10.4314/ijbcs.v14i6.9
- Sawadogo W.M., Dabire R.A., Ahissou B.R Bonzi S., Somda I, Nacro S., Martin C., Legrève A., Verheggen F. J. 2021. Comparison of life history traits and oviposition site preferences of *Tuta absoluta* for twelve common tomato varieties in Burkina Faso. **Physiological Entomology** 46 (3-4): 1-7. https://doi.org/10.1111/phen.12373
- Sawadogo W.M., Ahissou B.R., Somda I., Nacro S., LegrèveA & Verheggen F. (accepted) Identification of alternative hosts of the tomato leafminer in West Africa. **African Entomology**
- Ahissou, B. R., Sawadogo, W. M., Bokonon-, A. H. Somda I., Verheggen F. 2021. Integrated pest management options for the fall armyworm *Spodoptera frugiperda* in West Africa : Challenges and opportunities . A review. Biotechnol. Agron. Soc. Environ., 25(3), 192–207. https://doi.org/10.25518/1780-4507.19125
- Ahissou, B. R., Sawadogo, W. M., Bonzi, S., Baimey, H., Somda, I., Bokonon-Ganta, A. H., & Verheggen, F. J. 2021. Natural enemies of the fall armyworm Spodoptera frugiperda (Smith) (Lepidoptera: Noctuidae) in Burkina Faso. Tropicultura 2295-8010, 39(1). https://doi.org/10.1653/024.103.0414
- Ahissou, B. R., Sawadogo, W. M., Bokonon-Ganta, A. H., Somda, I., Kestemont, M. P. & Verheggen, F. J. 2021. Baseline Toxicity Data of Different Insecticides against the Fall Armyworm Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae) and

Control Failure Likelihood Estimation in Burkina Faso. African Entomology, 29(2), 435–444. https://doi.org/10.4001/003.029.0435

2. Présentations orales

- Sawadogo W. M., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer : Evidence from Burkina Faso. 2$^{\text{éme}}$ journée scientifique de l'université de Ouahigouya : Quel apport de la recherche scientifique face à la problématique de la gestion des ressources naturelles au Burkina Faso ? Du 08-09 décembre 2020 à l'Université de Ouahigouya, Burkina Faso.
- Sawadogo W. M., Mano E., Ahissou B.R., Somda I., Nacro S., Legreve A., Verheggen F. *Nesidiocoris tenuis* in Burkina Faso: Distribution, predatory capacity and insecticide sensibility. 4$^{\text{ème}}$ colloque scientifique international de l'Université de Kara. Consommation locale et valorisation des savoirs endogènes : quelles contributions des universités africaines pour renforcer la résilience des populations face aux crises planétaires ? Du 18 au 22 octobre 2021 à l'Université de Kara au Togo.
- Sawadogo W. M., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso. XIII$^{\text{ème}}$ Edition du FRSIT : Forum national de la Recherche Scientifique et Innovations Technologiques. Du 26 au 30 Octobre 2021 à l'Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso.
- Sawadogo W. M., Mano E., Ahissou B.R., Somda I., Nacro S., Legreve A., Verheggen F. *Nesidiocoris tenuis* in Burkina Faso: Distribution, predatory capacity and insecticide sensibility. XIII$^{\text{ème}}$ Edition du FRSIT : Forum national de la Recherche Scientifique et Innovations Technologiques. Du 26 au 30 Octobre 2021 à l'Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.
- Sawadogo W. M., Mano E., Ahissou B.R., Somda I., Nacro S., Legreve A., Verheggen F. *Nesidiocoris tenuis* in Burkina Faso: Distribution, predatory capacity and insecticide sensibility. IV$^{\text{ème}}$ Edition du SYST : Symposium International sur la Science et la Technologie. Du 15 au 19 Novembre 2021 à l'Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.
- Sawadogo W. M., Somda I., Verheggen F. Dynamique des populations de la mineuse de la tomate, *Tuta absoluta* Meyrick dans les zones subsaharienne et Sud-Soudanaise

du Burkina Faso. IV^{ème} Edition du SYST : Symposium International sur la Science et la Technologie. Du 15 au 19 Novembre 2021 à l'Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.

- Sawadogo W. M., Mano E., Ahissou B.R., Somda I., Nacro S., Legreve A., Verheggen F. Nesidiocoris tenuis in Burkina Faso: Distribution, predatory capacity and insecticide sensibility. Colloque International sur la Protection des Végétaux en Afrique. Ouagadougou, Burkina Faso du 30 novembre au 4 décembre 2021
- Sawadogo W. M., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. Insecticide susceptibility level and control failure likelihood estimation of Sub-Saharan African populations of tomato leafminer: Evidence from Burkina Faso. Colloque International sur la Protection des Végétaux en Afrique. Ouagadougou, Burkina Faso du 30 novembre au 4 décembre 2021
- Sawadogo W. M., Ahissou B.R., Somda I., Nacro S., Legreve A., Verheggen F. Identification of alternative hosts of the tomato leafminer in West Africa. Colloque International sur la Protection des Végétaux en Afrique. Ouagadougou, Burkina Faso du 30 novembre au 4 décembre 2021

3. Posters

- Sawadogo W. M., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. Criblage de pesticides homologués contre *Tuta absoluta* au Burkina Faso. Concours du meilleur poster édition 2021 Doctorants de l'Université Nazi Boni.
- Sawadogo W. M., Ahissou B. R., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. Niveau de sensibilité de la mineuse de la tomate (*Tuta absoluta*) à divers biopesticides. Colloque International sur la Protection des Végétaux en Afrique. Ouagadougou, Burkina Faso du 30 novembre au 4 décembre 2021
- Sawadogo W. M., Mano E., Ahissou B. R., Somda I., Nacro S., Legrève A.L. & Verheggen F. J. *Nesidiocoris tenuis* au Burkina Faso : Distribution, capacité de prédation et sensibilité aux insecticides. Colloque International sur la Protection des Végétaux en Afrique. Ouagadougou, Burkina Faso du 30 novembre au 4 décembre 2021

4. Questionnaire d'enquête

L'impact de Tuta absoluta sur la tomate au Burkina Fao

février -- Septembre- 2019

Il s'agit de mesurer l'impact de Tuta absoluta sur la production de tomate au Burkina Faso

Identification

localité; producteur

1. province

2. le village

3. le site maraicher

4. Coordonnée géographique

5. nom et prénom du producteur (éventuellement numéro de téléphone)

6. sexe

○ 1.F ○ 2.M

7. Type de mains d'œuvre utilisé

☐ 1. Familiale ☐ 2. employer ☐ 3. aucun

Vous pouvez cocher plusieurs cases.

8. Niveau d'étude

☐ 1. primaire ☐
2. secondaire ☐
3. universitaire
☐ 4. illettré
☐ 5. arabe
☐ 6. alphabétisation
☐ 7. formation agricole (formation classique, CEP, PD, parcelles vitrines...)

Vous pouvez cocher plusieurs cases (4 au maximum).

9. Nombre d'année d'expérience en terme de production de tomate

10. quelle est la superficie emblavée ○ 1. .... ha

11. quelles sont les variétés que vous avez produits

☐ 1. Cobra ☐ 2. Mongal ☐ 3. Petomech
☐ 4. Tropimech ☐ 5. Raïssa ☐ 6. Jampakt
☐ 7. .... ☐ 8. ....

Vous pouvez cocher plusieurs cases.

Connaissance de Tuta absoluta

savoir si le producteur connait Tuta absoluta

12. Connaissez-vous Tuta absoluta (l'enquêteur doit lui monter un adulte et une larve dans la feuille)

○ 1. Oui ○ 2. non

13. depuis quand (année) cet insecte a infesté votre champs ou votre de production

○ 1. cette année (2019) ○ 2. 2018 ○ 3. 2017
○ 4. 2016 ○ 5. 2015 ○ 6. 2014
○ 7. 2013 ○ 8. 2012 ○ 9. 2011
○ 10. 2010

14. quelles sont les spéculations que cet insecte attaque (plante cultivé y compris plante non cultivée)

☐ 1. Pomme de terre ☐ 2. Oignon
☐ 3. poivron ☐ 4. aubergine
☐ 5. aubergine africaine ☐ 6. chou
☐ 7. laitue ☐ 8. haricot vert
☐ 9. piment ☐ 10. mente
☐ 11. maïs ☐ 12. patate
☐ 13. concombre ☐ 14. melon
☐ 15. gombo ☐ 16. aucun

Vous pouvez cocher plusieurs cases.

15. quelles sont les organes de la plante que l'insecte attaque?

☐ 1. Tige ☐ 2. feuille ☐ 3. fruits
☐ 4. fleure ☐ 5. ....

Vous pouvez cocher plusieurs cases.

16. quelle est la proportion de dégâts de Tuta absoluta sur les organes végétatifs (feuilles, tiges, fleure)au moment de la première récolte de la tomate

○ 1. pour < 25% ○ 2. entre 25 et 50%
○ 3. entre 50 et 75% ○ 4. entre 75 et 100%

17. Par rapport à ce que vous gagnez avant cet insecte, quel est la quantité de fruits que vous pensiez récolter (déterminer la masse en kg avec lui)

18. quelles est la quantité de fruits réellement obtenue avec la présence de ce ravageur (déterminer la masse en kg avec lui)

19. quelle est la quantité de fruit triée du fait des perforation de Tuta absoluta (déterminer la masse en kg avec lui)

20. Par rapport à ce que vous gagnez avant l'invention de Tuta absoluta, combien de francs espériez-vous gagner?

21. Combien de francs avez-vous eu avec les dégâts de Tuta absoluta?

22. avez-vous eu un bénéfice ? ○ **1. oui** ○ **2. non**

23. Quel impact cette pertes peut-elle avoir sur votre vie social et économique?

les mesures de protections phytosanitaire

connecter les méthodes de traitements phytosanitaires et les politiques mises en œuvres pour la réalisation

24. Avez-vous déjà reçus une formation sur les mesures de protection phytosanitaires
○ **1. oui** ○ **2. non**

25. comment faites-vous pour lutter contre ce ravageur? ☐ **1. arrachage et destruction des plantes infestées** ☐ **2. utilisation d'insecticides chimiques de synthèse** ☐ **3. insecticides biologiques**
☐ **4. vides sanitaires (au moins 6 semaines)**
☐ **5. rotation**
☐ **6. désherbage**
☐ **7. désinfection des sols (solarisation)**
☐ **8. prédateur**
☐ **9. parasitoïdes**
☐ **10. plante attractive**
☐ **11. plante répulsive**
☐ **12. piégeage de masse**
☐ **13. ....**
☐ **14. ....**
☐ **15. ....**
Vous pouvez cocher plusieurs cases.

26. quels insecticides utilisez vous

27. combien de traitement insecticides faisiez-vous avant l'arrivée de cet insecte durant le cycle de production de la tomate?

28. Combien de traitement faites-vous avec l'arrivée de cet insecte

29. quelles doses d'insecticides appliquées à l'Ha
☐ **1. ....** ☐ **2. ....**
☐ **3. ....**☐ **4. .... _**
☐ **5. ....**☐ **6. ....**
Vous pouvez cocher plusieurs cases.

30. Trouvez-vous facilement les produits phytosanitaire sur le marché ?
○ **1. oui** ○ **2. non**

31. est-ce que les pesticides sont efficaces? Lesquels?

32. quels sont les pesticides inefficaces (qui ne tue pas Tuta absoluta)?

33. en cas de rotation? quelle spéculation utilisez-vous?

34. en cas de désherbage quelle techniques utilisez vous
☐ **1. manuel** ☐ **2. herbicide** ☐ **3. mécanique**
Vous pouvez cocher plusieurs cases.

35. Constater vous ou utilisez un prédateur pour la lutte? si oui quel est son nom?

36. Avez-vous remarquer une plante qui attire Tuta absoluta plus que la tomate?
☐ **1. ....** ☐ **2....................................._**
☐ **3. ....** ☐ **4....................................._**
☐ **5. .... __**
Vous pouvez cocher plusieurs cases.

37. Connaissez-vous une plante qui repousse Tuta absoluta?
☐ **1. ....** ☐ **2. ....**
☐ **3. .... _** ☐ **4. ....**
☐ **5. ....**
Vous pouvez cocher plusieurs cases.

38. Faites-vous le piégeage de masse? si oui avec quel produit?
☐ **1. ....** ☐ **2. ....**
☐ **3. .... _** ☐ **4. ....__**
☐ **5. ....**
Vous pouvez cocher plusieurs cases.

39. Avez-vous des soutiens quelconques pour lutter contre ce ravageur ?
○ **1. oui** ○ **2. non**
Aller à '42-Avez-vous des attentes' si Avez-vous des soutiens quelconques = "non"

40. D'où proviennent ces soutiens ?

☐ **1. autorité administrative** ☐ **2. ONG/projet**
☐ **3. famille** ☐ **4. ....**
☐ **5. ....** ☐ **6. ...._**

Vous pouvez cocher plusieurs cases.
La réponse est obligatoire.

41. Quelle est la nature de ces soutiens ? (matériel ou financier

☐ **1. Technique** ☐ **2. Matériel** ☐ **3. financier**

Vous pouvez cocher plusieurs cases.

42. Avec l'avènement de ce ravageur quelle suggestion faites vous

☐ **1...**
☐ **2.._**
☐ **3...__**
☐ **4...___**
☐ **5..____**

Vous pouvez cocher plusieurs cases.