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Plant resources in the control of the key food pests Andean potato weevils (*Premnotrypes* spp.) and coffee berry borer (*Hypothenemus hampei*): a systematic review

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Abstract. Potato and coffee crops grapple with pronounced challenges posed by pests, notably the Andean potato weevils (*Premnotrypes* spp.) and the coffee berry borer (*Hypothenemus hampei*). These pests inflict significant economic repercussions on both smallholder and commercial farmers by disrupting essential food supply chains. This review delves into the insecticidal potentials of botanical resources against these pests. Notably, extracts and essential oils (EOs) from native flora or commercially available in each affected country have compelled efficacy against *Premnotrypes vorax*, *P. latithorax* and *Hypothenemus hampei*, such as *Schinus molle* L. and *Schinus terebinthifolia* Raddi, respectively. Through rigorous laboratory tests, on-site evaluations, and cost-effectiveness assessments, there emerges a strong advocacy for these botanical solutions. They present not only a sustainable countermeasure to these pests but also a greener alternative to conventional pesticides, thereby potentially reducing the environmental degradation and health concerns synonymous with chemical pesticides. The shift towards natural pesticides, especially those derived from plants like S. molle and S. terebinthifolia, is not only

environmentally strategic but also economically prudent, aligning with both market trends and long-term environmentally strategic but also economically prudent, aligning with both market trends and long-term sustainability goals.

Key words: sustainability, pest management, insecticidal activity, essential oils, plant extracts.

INTRODUCTION

Damage to agricultural produce inflicted by pests during growth or storage phases markedly diminishes global food supplies. Such losses intensify food scarcity challenges, particularly in regions already grappling with low human development indices (Savary et al., 2019). The United Nations reports that approximately 13% of food is lost from harvest to retail, with an estimated 17% of global food production going to waste, including 11% in households, 5% in food service, and 2% in retail (United Nations, 2022). Potatoes are grown on both a small and large scale in different countries around the world, especially China and India (Asia), Ukraine and Russia (Europe), Egypt and Algeria (Africa), and the USA and Peru (America), being an essential component of traditional foods and fast food chains worldwide scope (Devaux et al., 2021; FAO, 2022). In addition, potatoes also have nutraceutical potential, with some varieties known for their high antioxidant activity (Gil-Rivero et al., 2019). However, the presence of agricultural pests dramatically reduces the supply of this product, affecting the supply to consumers and harming suppliers. Among the main potato pests are those of the genus *Premnotrypes* (*Curculionidae*), which in turn are coleopterans known as Andean potato weevils (El gorgojo de los Andes), affecting plantations located mainly in Colombia, Venezuela, Bolivia, Ecuador and Peru (Bragard et al., 2020). These beetles feed on the roots of plants, which can lead to a reduction in the productivity and quality of crops. In addition, *Premnotrypes* larvae cause internal damage to potato tubers (*Solanum tuberosum*), making them unsuitable for human or animal consumption (Pérez-Álvarez et al., 2010). These pests are restricted to the highlands of the tropical Andes, so that the adults feed on leaves by making cuts on the leaflets edges, whereas the larvae have subterranean cycle and feed on tubers. Moreover, the biological cycle is univoltine and synchronized with the potato phenology (Loayza-Huillca et al., 2023).

As another example, coffee (*Coffeea arabica*) stands as one of the world's most extensively enjoyed beverages, so its seed has been introduced and well adapted to several continents, in which today there are major coffee grains exporting countries, such as Brazil, Colombia and Honduras (Americas), Vietnam, Indonesia and India (Asia), and Ethiopia and Uganda (Africa), so that the global production reached 168.5 million 60-kilogram bags as of 2021/2022, moving about US$ 88.3 billion (FAO, 2023; Triolo et al., 2023; WPR, 2023). However, local plantations are severely affected by the coleopteran *Hypothenemus hampei* (*Scolytidae*), also known as coffee berry borer (La broca del café), which can cause significant damage to coffee beans, reducing the quality and yield of the harvest (Abewoy, 2022). The damage to the coffee occurs when the female beetle bores a hole into the fruit and eventually into the seed, creating builds galleries for reproduction, followed by larval feeding on the endosperm (Vega et al., 2015; Damon, 2000).

Currently, for the control of these two pests, pesticides of synthetic origin are mostly used, for example, carbofuran and endosulfan, respectively, which, despite being efficient, have already shown the emergence of resistance, in addition to the residual effects on the environment and consumers (Montesdeoca & Gallegos, 2009). Carbofuran is related to human erythrocyte membrane toxicity (Sharma et al., 2012), as well as acetylcholinesterase inhibition caused by occupational exposition (Gammon et al., 2012), and an acute pancreatitis case (Rizos et al., 2004), whereas endosulfan is associated with harmful side effects on humans, causing male infertility due to testicular atrophy and reduced sperm count (Sebastián & Raghavan, 2015). Due to these causes, more sustainable control measures have been advocated, which includes agricultural practices covered by the current term Integrated Pest Management (IPM). Recent articles exemplify the use of these practices to benefit plantations, such as the intercropping practice adhesion (Lepse & Zeipina, 2023), crop rotation for natural pest predators installation (Talgre et al., 2023), the use of pest controlling fungi as *Beauveria* and *Trichoderma* genus (Mahfudz et al., 2019; Novikova et al., 2021), as well as the use of botanical resources with insecticidal activity, such as essential oils (EOs) and plant extracts (Mawussi et al., 2009; Jankevica et al., 2018; Smith & Perfetti, 2020), which can be used directly or through formulations that increase their efficiency, as is the case of nanoemulsions (Echeverria & Albuquerque, 2019). In this sense, it is essential to increase the number of studies with local plants and/or with high availability, including their products and their periodic compilation, to better channel the information. Therefore, this review aims to analyze the various studies on the use of products of plant origin as a sustainable alternative insecticide against the pests *Premnotrypes vorax*, *P. latithorax* and *Hypothenemus hampei*, which are of agricultural importance in several countries.

PLANT RESOURCES WITH INSECTICIDAL ACTIVITY

Against *Premnotrypes* spp

Schinus molle L. is a very distributed species in South America, mainly in the Peruvian territory. Its aqueous extract from leaves (one year old) obtained by hydrosol steam drag method presented insecticidal activity against several stages of *Premnotrypes vorax* development, so 5% concentration caused 50% mortality in adults in 24 h. Moreover, the extract at the concentration of 10% caused 25% inhibition of egg hatching at 24 h. Although the mortality rates did not surpass 50% in adults in 24 hours, using *S. molle* extract could be considered a reasonable alternative for managing this pest (López et al., 2017). Moreover, the EO extracted from *S. molle* leaves was tested by fumigation for its impact on adult and larval mortality, larval hatching inhibition, and antifeedant activity. Results showed that an 8% concentration yielded a 36.67% mortality rate for adults and larvae, 94.78% antifeedant activity, and 80% larval hatching inhibition within 24 hours (Peña Caiza, 2018). Field tests were conducted to assess the EO's commercial potential. Applying a 15% dilution of *S. molle*'s EO yielded promising outcomes, including a reduction in the incidence (30.07%) and severity (17.07%) of white worms, and it led to the growth of plants with larger tuber diameters (4.88 cm) and higher yields (5.35 kg treatment^{-1}). Furthermore, the treatment showed a favorable cost-benefit ratio, with net gains of approximately 0.42 times the amount invested (Cortez Villarroel, 2018).

In another investigation regarding EOs from *Coriaria thymifolia* Humb. & Bonpl. ex Willd. (aerial parts), *Clinopodium tomentosum* (Kunth) Govaerts (leaves and flowers), and *Euphorbia helioscopia* L. (aerial parts) exhibited effective activity against *P. vorax* larvae. They were analyzed at concentrations ranging from 0.5% to 2% throughout 24 to 72 hours. Of particular note were the EOs from *C. tomentosum* and *E. helioscopia* at a 2% concentration, which led to 100% larval mortality within 24 hours. The EO from *C. thymifolia* achieved a similar result in 48 hours (Urquizo Nachimba, 2017).

The Andean species, *Minthostachys spicata* (Benth.) Epling and *Clinopodium bolivianum* (Benth.) Kuntze were tested against *Premnotrypes latithorax* due to the considerable larvicidal activity the EOs derived from their aerial parts exhibited. After 24 hours, the LC_{50} and LC_{90} values for *M. spicata* were found to be 0.040 and 0.095 µL cm^{-2}, respectively, whereas for *C. bolivianum* , these values were 0.088 and 0.248 µL cm^{-2}. The main compounds in *M. spicata* EO were identified as pulegone, isomenthone, and menthone, whereas isomenthone, thymol, and menthone were the predominant compounds in *C. bolivianum* EO (Solís-Quispe et al., 2018).

Additionally, the leaf oils from *C. bolivianum* and *Eucalyptus globulus* Labill. were found to have insecticidal activity against *P. vorax*. These oils were tested in the field at a 6 mL L^{-1} concentration to evaluate their effects in natural conditions. The EO from *C. bolivianum* achieved a population reduction of 55.8%, while the EO from *E. globulus* led to a reduction of 36.6%. The damage inflicted by the larvae was found to be 3,988.98 and 4,672.49 kg h^{-1} for *C. bolivianum* and *E. globulus*, respectively, so that the treatments were applied at the time of emergence and, later, at the pre-flowering time. The primary constituents of *C. bolivianum* EO were identified as isomenthone, carvacrol, and 1,8-cineole, while the EO from *E. globulus* mainly contained *α*-pinene and 1,8-cineole (eucalyptol) (Rojas Roque, 2007).

Research by Baldeón Ordóñez highlighted the insecticidal effects of EOs from three species of *Tagetes* against *P. vorax*: *T. minuta*, *T. terniflora*, and *T. zypaquirensis*. When tested on the larval stage at concentrations ranging from 0.2% to 1.0%, *T. zypaquirensis* EO displayed the most effective activity after seven days of treatment with a 0.8% concentration, resulting in a 77.77% mortality rate. After 21 days, *T. minuta* and *T. zypaquirensis* EOs resulted in 100% mortality, while *T. terniflora* achieved 88.89% mortality (Baldeón Ordóñez, 2012). Lastly, garlic (*Allium sativum* L.) extract (at 20%) and oil (500, 1,000, and 1,500 ppm) were tested against adult *P. vorax* by applying them to potato foliage over an eight-day period. The oil treatment resulted in a high mortality rate (96% – 100%), while the extract treatment yielded a mortality rate of less than 50% (Romero Alvino, 2021).

Against *Hypothenemus hampei*

Numerous EOs have been found to exhibit substantial insecticidal activity against *Hypothenemus hampei*. For instance, the aerial parts EO from *Ocimum canum* Sims resulted in a lethal dose (LD_{50}) of 320 ppm over 24 hours against adult Coleoptera. The oil's primary constituents were the monoterpenoids (4-terpineol and linalool) (Mawussi et al., 2012). Similarly, an emulsion of *Aeollanthus pubescens* Benth. EO demonstrated an LD_{50} of 220 ppm within 24 hours, with linalool and fenchone as the predominant compounds (Mawussi et al., 2009).

Mendesil et al. (2012) research evaluated the insecticidal activity of eleven EOs derived from various species against *Hypothenemus hampei*, of which six EOs exhibited notable efficacies. *Thymus vulgaris* L., *Ruta chalepensis* L., *Chenopodium ambrosioides* L., and *Cymbopogon nardus* (L.) Rendle induced a mortality rate between 80% and 90% within 24 hours. Meanwhile, *Mentha spicata* L. led to a 60% mortality rate within the same timeframe, whereas *Aloysia* sp. yielded an 87.5% mortality rate within 48 hours. These experiments were conducted by immersing samples (1% in ethanol) in filter paper (Mendesil et al., 2012).

The EO from the leaves of the sandbank plant *Schinus terebinthifolia* Raddi also exhibited insecticidal activity, resulting in 100% mortality in a surface contamination test at a 1% concentration over 24 hours. Using the same concentration and timeframe, the EO demonstrated 97.5% mortality in a direct contact test (Santos et al., 2013). Other Brazilian species such as *Pogostemon cablin* (Blanco) Benth. has also shown promising activity against *Hypothenemus hampei*. Its EO had an LD_{50} and LD_{90} of 19.20 (14.50–24.50) and 141.00 (85.00–318.00) $\mu g\ mg^{-1}$ of insect, respectively, after 24 hours. For the EO-based emulsion, these values were 28.60 and 96.90 $\mu g\ mg^{-1}$ of insect, respectively. The lethal time was approximately 10 minutes. Tests conducted via direct contact revealed changes in female development, including modifications in reproduction and feeding, increased walking activity, and histopathological alterations in the midgut. The oil's primary compounds were patchoulol, *α*-guaiene, and *α*-bulnesene (Santos et al., 2022).

Eucalyptus resinifera Sm. (Myrtaceae) also demonstrated insecticidal solid activity against adult females, especially in a fumigation test. The leaf EO achieved an LC_{50} of 64.72 $\mu L\ L^{-1}$ of air after 24 hours, which was more efficient than the positive control (garlic extract) that presented an LC_{50} above 700 $\mu L\ L^{-1}$ of air. The LT_{50} value (lethal time causing 50% mortality) was approximately 4 minutes. The oil's main compounds were 1,8-cineole (59.3%), *p*-cymene (12.9%), and *α*-pinene (9.7%), with a high yield of 2.45%. These three substances, mainly responsible for the biological activity, exhibited synergistic effects. The biological activity of the EO and the compound mixture was statistically equal and far more efficient than the individual compounds or a two-compound mixture (Reyes et al., 2019).

Lastly, the aerial parts EO from *Minthostachys mollis* Griseb. (0.5%) resulted in 100% pest mortality within 18 hours. Its main compounds (menthone, pulegone, and caryophyllene) were also evaluated. Only pulegone achieved 100% mortality in 72 hours, whereas menthone and caryophyllene resulted in 85% and 50% mortality, respectively. Interestingly, the insecticidal activity was higher using the immersion method compared to the spray method, resulting in a mortality rate of only 52% at the identical concentration (Benites et al., 2018; Calle-Álvarez et al., 2004).

Moreover, a formulation comprising neem oil (*Azadirachta indica* A. Juss.) and *d*-limonene was tested against *Hypothenemus hampei* by filter paper contact, direct contact, and aspersion in a coffee plantation. When assessed for insecticidal activity, the formulation, diluted to a 1.12% concentration in water, caused 63.34% and 100% mortality rates after 48 hours, via filter paper contact and direct contact, respectively. In the field, the formulation reduced the *Hypothenemus hampei* population by 62.4% after 60 days (with treatments applied every 20 days), compared to the negative control (Brito et al., 2021).

Additional formulations combining various components have also demonstrated activity against *Hypothenemus hampei*, with coconut (*Cocos nucifera* L.) oil being a common major compound used in concentrations between 2% – 5%. The formulation containing coconut shell wood vinegar and 5% clove (*Syzygium aromaticum* (L.) Merrill & Perry) oil caused mortality rates between 80% – 95%. In contrast, the formulation comprising coconuts shell wood vinegar and 5% citronella (*Cymbopogon nardus* (L.) Rendle) oil achieved mortality rates between 73.34% – 88.33% after five days (Indriati & Puspitasari, 2021).

Other considerations

Our analysis underscores these botanical agents' pivotal role as both efficacious and environmentally friendly alternatives to conventional pest control methods. Notably, many potent plants identified are distributed worldwide, emphasizing biodiversity's untapped potential in reshaping sustainable agriculture's future. Given the increasing global demand for sustainable agricultural practices, there is a burgeoning need for interdisciplinary research integrating botany, biochemistry, and agronomy findings. The highlighted studies also underscore the importance of extending research beyond mere identification to understanding the mechanisms of action and probable active substances, optimizing extraction processes, and developing efficient delivery systems for these botanical agents. Furthermore, recognizing the economic implications, there's an avenue for researchers to delve into the cost-effectiveness and scalability of these natural solutions. With a growing global emphasis on reducing the carbon footprint, the cultivation, production, and application of these indigenous plant-derived products could also bolster local economies, supporting farmers and creating job opportunities in the producer regions.

Numerous botanicals, such as *S. molle*, have demonstrated significant insecticidal activity against *Premnotrypes*, as highlighted in this review. Their abundance and ease of cultivation offer a potential substitute alternative for pest management. While the aqueous extract of *S. molle* may not have demonstrated high adult mortality rates (50% in 24 hours, using a concentration of 5%), it could still be an effective tool in pest management, potentially reducing the pest population by half and somewhat impacting egg hatching. Conversely, the plant's essential oil was more effective in deterring feeding and inhibiting egg hatching, with studies conducted by Cortez Villarroel (2018) further validating its economic effectiveness in potato crops. The more polar extracts of *S. molle* contain high concentrations of tannins, phenolics, and catechins (Cortez Florentino, 2018). These compounds are known to act as digestive enzyme inhibitors in insects due to their protein-binding ability (Hanhineva et al., 2010). Moreover, catechin may disrupt ion transport in larvae because of harm to the anal papillae and outer cuticle layer (Elumalai et al., 2016).

The EO of *S. molle*, abundant in Latin American countries, primarily consists of compounds like α-phellandrene, β-phellandrene, α-pinene, β-pinene, limonene, p-cymene, and myrcene (López de La Cruz & Caso Orihuela, 2015). Monoterpenes, such as α-pinene and p-cymene, are known to disrupt cellular membrane function due to their low polarity, thus breaking down the lipid bilayer (Salakhutdinov et al., 2017). These compounds can also easily penetrate target organisms' respiratory systems (Langsi et al., 2020). Limonene has also been found to inhibit oviposition and egg-hatching of insects due to its repellency and toxicity (Karr & Coats, 1988). Similarly, α-phellandrene harms vital insect organs, including the cuticle, brain, midgut, and fat body (Chaaban et al., 2019) while exhibiting larvicidal activity (Evergetis et al., 2013). Apart from *S. molle*'s essential oil, oils from *C. thymifolia*, *C. tomentosum*, and *E. helioscopia* also exhibited significant efficacy against *Premnotrypes* larvae. Recurring major substances in other active species, such as menthone, isomenthone, and 1,8-cineole, along with pulegone and carvacrol, have displayed high insecticidal or larvicidal properties in their isolated forms (Kumar et al., 2011). Compounds like 1,8-cineole can inhibit acetylcholinesterase activity in insects (Abdelgaleil et al., 2009; Kumar et al., 2011). In their turn, the EO's ketone compounds menthone and pulegone are $GABA_A$-R (Gama amino butyric acid A receptor) negative allosteric modulators, so that this receptor is one of the mains insecticide targets and is related to inhibition of nervous central system (Sánchez-Borzone et al., 2017). Furthermore, it was demonstrated that carvacrol is a potent inhibitor of the housefly [14C]-nicotine acetylcholine receptors binding in a non-competitive pattern, which is probably related to the toxic effect on the insect's nervous system (Tong et al., 2013).

When considering activity against *Hypothenemus hampei*, plants such as *T. vulgaris*, *R. chalepensis*, *C. ambrosioides*, and *C. nardus* displayed high mortality rates within 24 hours. Similar outcomes were observed with the EO from *S. terebinthifolia*, a species with the same genus as *S. molle*, also presenting wide distribution throughout the American continent (Clemente, 2006; Santos et al., 2009). As with *Premnotrypes*, oils rich in 1,8-cineole, pulegone, and menthone exhibited considerable activity against *Hypothenemus hampei*. In addition, other well-known insecticidal extracts and products, including citronella oil, neem (*A. indica*), and limonene, demonstrated activity against *Hypothenemus hampei*. Citronella oil interferes with haemocytes viability and inhibits acetylcholinesterase activity due to its principal monoterpenes (Aftab & Hakeem, 2021; Johnson et al., 2021). Neem affects insect development and reproduction, such as feeding, hormone function in juvenile stages, and molting processes, primarily attributed to its terpenoids (Brahmachari, 2004).

The synergism between specific components of EOs and between EOs from different species is well known (Mossa, 2016). Therefore, studies are suggested to verify the association of two or more EOs that present major compounds with different mechanisms of action. For *Premnotrypes* genus, the interaction between oils such as *S. molle* and *M. spicata* could be evaluated, since both plants are widely found in American countries. In the case of *H. hampei*, associations between *E. resinifera*, *M. mollis* and between them and neem could be interesting if evaluated in assays similar to those presented in this review.

The recurrent losses in key crops like potatoes and coffee due to pests underscore the need for sustainable and effective pest management solutions. Recognizing the dual challenges of economic and environmental sustainability, there is a pronounced move towards natural pesticides. Plants like *S. molle* and *S. terebinthifolia*, distributed in several countries worldwide, have shown potential as sources of organic pesticides (Vicenço et al., 2020). On the other side, synthetic pesticides have been linked to health issues in farm workers and local communities (Ayilara et al., 2023) and despite are effective in the short term, come with recurring costs. Also, the adverse environmental effects of synthetic pesticides, such as soil degradation and water contamination, can be mitigated by natural alternatives reducing the associated long-term environmental remediation costs (Pathak et al., 2022). Furthermore, increased resistance necessitates higher dosages and frequent applications, so adopting botanical alternatives can reduce these health risks, leading to a healthier, more productive workforce, and potentially lower public health expenses. As of 2020, the global pesticide market size was valued at over USD 55 billion (Fridonia Group, 2021). Transitioning to abundant local plants like *S. molle* can be more cost-effective in the long run, reducing dependence on imported synthetic chemicals (Bañuelas, 2018). Moreover, natural pesticides often work through diverse modes of action, reducing the likelihood of pests developing resistance and ensure long-term applicability and economic sustainability (Procópio et al., 2015; Tang et al., 2020). Since biological controllers from plants are obtained from organic producers who cultivate species in a standardized way, the risk of deforestation and environmental contamination is considered inexistent (Gamage et al., 2023). Beside this, the organic food market has been witnessing robust growth. By 2021, organic sales reached nearly USD 57.5 billion globally. Producers can tap into this burgeoning market by utilizing natural insecticides, positioning their products as sustainably grown and attracting premium prices (Waltover, 2023).

Finally, the studies described in this review can serve as a basis for the production of pest biocontrollers that are in accordance with sustainability policy, which includes not only large agricultural exporters but also the market of local agricultural producers, so that they can increase the reliability of its products using low toxicity and efficient resources at an affordable cost to their realities.

CONCLUSION AND PROSPECTS

Different extracts and EOs have displayed insecticidal, larvicidal, or ovicidal activity against *Premnotrypes vorax*, *P. latithorax* and *H. hampei*. The promising outcomes from these studies indicate that these natural substances could potentially be used commercially and comprehensively in the future. The review discussion points to the need for further research into formulation studies for enhancing the efficiency of the active principles. Additionally, this review also serves as a springboard, highlighting the immense promise of botanical insecticides and urging stakeholders to harness the full potential of certain plants, such as *S. molle* and *S. terebinthifolia*. As we move towards a future where sustainability is paramount, the findings presented here act as a beacon, guiding researchers, policymakers, and agriculturalists to work collaboratively in realizing the vision of a greener, pest-free agricultural landscape. Furthermore, commitment is necessary between researchers from different areas involved in the topic, such as chemists, biologists, agronomists, and others, so that studies such as those presented in this review are directed towards a viable application of their respective products.

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