Review Article

Plant-Based Insecticides: A Review and Bibliometric Analysis

Comment [H1]: This review is about all Plant-Based Insecticides or onlyInsecticides againts*Sitophilus zeamais,Nasutitermes corniger* and*Aedes aegypti* species?

ABSTRACT

This work provides a review of the state of art and recent trends on the insecticidal activity of plant-based products against insect pests. In addition, a bibliometric analysis was carried out. Insect pests attack crops or transmit diseases and their uncontrolled growth is intensified by human activity, which affects natural ecosystems and trophic chains. *Aedes aegypti* L. transmits dengue, chikungunya, zika and yellow fever, while *Sitophilus zeamais*Motsch is a stored grain pest, and *Nasutitermescorniger*Motsch attacks trees and urban buildings. The population control of insects has primarily relied on synthetic insecticides with high environmental toxicity and whose effectiveness reduced due to the emergence of resistant insects. Otherwise, plant insecticides tend to be more biodegradable and less harmful to non-target organisms. They can impair the viability of embryos, larvae, pupae, or adults, as well as fertility and oviposition or feeding behavior. The bibliometric analysis revealed the concentration of researches on natural insecticides in tropical regions worldwide, where there is a strong occurrence of diseases transmitted by *Ae. aegypti*, which corresponded to the largest number of reports, compared to *N. corniger* and *S. zeamais*. Furthermore, the synthesis of metallic nanoparticles from plant products has strongly emerged as a current trend.

Comment [H2]: Briefly present the main results on the documents used

Comment [H3]: Not appropriate

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Comment [H5]: Does the review focus only on these insect species? It would be preferable to cite the most studied families

Keywords: Agricultural pest,disease vector, insect pests, natural insecticides, proteins, secondary metabolites

1. INTRODUCTION

The increase of human populations around the world resulted in growing demand for food and expansion of territories for human activity. Thus, natural ecosystems were modified, causing imbalance in trophic chains. Consequently, the imbalance of populations including plants, fungi, rodents, and insects cause unwanted impacts on the economy and public health [1,2]. Insect species are considered pests when they attack crops, compete for food, or transmit diseases to humans and/or other animals, and plants.

The main strategy to control insect populations still relies on chemical control using synthetic pesticides. However, the use of these chemicals may become ecologically dangerous because they can linger in soil and water for many years, accumulating in the food chain and causing further damage [3]. These effects can be exacerbated by the leaching of the synthetic pesticides to aquatic environments where they may cause deleterious effects for aquatic organisms and for species that have them as food sources [1, 4]. Additionally, the frequent use of insecticides that act through similar mechanisms can lead to the selection of resistant populations [5].

It is known that the insecticidal mechanisms of the synthetic compounds generally involve the inhibition of enzymes, neurotransmitters or ion channels activity that are conserved in humans [6, 7]. Thus, the handling and application of these chemicals expose the applicators, and individuals living in proximity to treated areas to the risk of physiological disorders, including Parkinson disease, Alzheimer, cardiovascular diseases, and a set of cancers [8,9].

Under this perspective, efforts have shifted to the search for natural compounds as an alternative to control insect pests since they tend to be less harmful than synthetic insecticides [10, 11]. In this work, we provide a review of generalities about insects that act as disease vectors, urban pests, or agricultural pests, as well as the activity of plant-based insecticides. In addition, trends in research on plant-based insecticides were assessed through a bibliometric approach.

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2. METHODOLOGY

2.1 RESEARCH AND CATALOGING OF SCIENTIFIC LITERATURE

The search was carried out in different databases such as science direct (sciencedirect.com/), scopus (https://www.scopus.com/), scielo (https://www.scielo.br/), google scholar (https://scholar.google.com/) and web of science (http://webofscience.com/) using the keywords: “plant extract”, “pesticides”, “Insect pests”, “Pesticides impact”, “Lectin”, “Protease Inhibitor”, “Secondary Metabolites”, “Pest Impacts”, “*Aedesaegypti*”, “*Sitophilus zeamais*”, and “*Nasutitermescorniger*”. Data from epidemiological bulletins provided by the Brazilian Ministry of Health were also consulted. Next, the titles and abstracts of original papers, review articles, books and book chapters were read, excluding those that did not provide relevant information or did not fit the scope of the investigation. Articles in Portuguese and English were used. This made it possible to carry out a bibliographical review that served as a theoretical foundation regarding the current context of the impact of insect pests, synthetic insecticides, and natural insecticides.

2.2 BIBLIOMETRIC ANALYSIS OF SCIENTIFIC DATA

Data collection for bibliometric analysis was carried out based on research using the keywords: “Plant Extract”; “Insecticide Activity”; “*Sitophilus zeamais*”; “*Nasutitermescorniger*”; “*Aedes aegypti*”, in the database Web of Science (https://www.webofscience.com/) with no defined publication period. All terms were searched in the “Topics” field, including title, abstract, authors, keywords and “keyword plus”, which is a feature of the platform that searches for terms frequently cited within articles. The operators “AND” were also used to relate to the keywords “Plant Extract” and “Insecticide Activity” and “OR” for “*Sitophilus zeamais*”; “*Nasutitermescorniger*”; “*Aedes aegypti*”, to include variations between work.

Based on the results, studies that were duplicates, did not use plant compounds, did not evaluate insecticidal activity, did not target the species *Sitophilus zeamais,Nasutitermescorniger* or *Aedes aegypti*, and review works were excluded.

Comment [H7]: This study is about all Plant-Based Insecticides or only this species?

After applying the exclusion criteria, the remaining data were entered into the VOSviewer software to generate graphs and figures that represent the analysis of bibliometric parameters such as co-authorship relationships, between among authors, countries and co-occurrence of keywords used in the papers, as well as the strength of correlation of these parameters.

3. *AEDES AEGYPTI* AND ITS MEDICAL IMPORTANCE

Many arthropod species can act as disease vectors for humans (Table 1), thus, an important strategy for the epidemiological control of diseases imply the reduction of vector populations to ecologically acceptable levels. Some examples of diseases transmitted by arthropods and considered as serious public health concerns worldwide are dengue, zika, chikungunya and yellow fevers [12, 13]. The main vector of these arboviruses (viral diseases carried by arthropods) is the mosquito *Aedes aegypti* [14].

Table 1. Disease vectors and control methods

Insect	**Pathology**	**Control method**	**Reference**
Ae. aegypti L.	Dengue, zika chikungunya, yellow fever	Chemical interventions using larvicides and insecticides. Introduction of sterile male mosquitoes to reduce the reproduction rate.	Pliego-pliego et al. [15]
Culex quinquefasciatus Say	Lymphatic Filariasis	Chemical interventions using larvicides. Use of protection nets treated with long term insecticides.	Rai et al. [16]
Triatominae Subfamily (Hemiptera: Reduviidae)	Chagas disease	Application of insecticides (pyrethroids)	Gürtler and Cecere, [17]
Lutzomyia genus	Leishmaniasis	Pulverization of chemicals	Barbosa et al. [18]; Rocha et al. [19].
Anopheles gambiae Giles	Malaria	Pulverization of residual products and use of protection nets treated with insecticides	Collins et al. [20]

In 2022, 1.450.270 probable dengue cases were recorded in Brazil, with 1.016 deaths. For zika and chikungunya fevers, the records were lower, but the agencies responsible for the epidemiological control suggest continuous monitoring to prevent the resurgence of these diseases [21]. In contrast, in the early months of 2023, 899.000 probable cases of dengue fever were registered. This datum represents an increase of 30% in comparison with the same period in 2022 [21]. In addition, these diseases account for economic losses by the affected countries that need to invest in strategies to mitigate them. Only in 2013, the costs associated with the dengue treatment, not counting expenses with vector control, reached US$ 1,228,000.00 [22].

Aedes aegypti Linnaeus, 1762 (Diptera, Culicidae) is native from the African continent. Its acclimatization was mainly driven by anthropic impacts on the natural environment that already favored survival in spaces occupied by humans [23]. *Ae. aegypti* has a pair of functional wings and another pair modified for balance structures (Figure 1A). The black color together with the white marks in the lines formed on the mosquito thorax are characteristic of the species [13]. Males of *Ae. aegypti* feed on nectar, while females have a daytime blood-sucking habit. The bite of the females can transmit dengue, yellow fever, zika or chikungunya viruses [13].

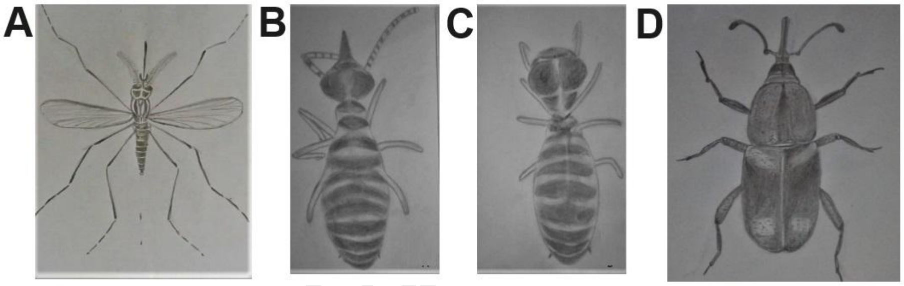

Figure 1. *Aedes aegypti* in adult winged phase (A).*Nasutitermescorniger*Soldier (B) and worker (C)*. Adults of Sitophilus zeamais*, the maize weevil (D)

The oviposition sites of *Ae. aegypti* are associated with standing water, with a preference for reservoirs containing clean water. But it is also adapted to reproduce in environments with non-good quality water. After the copulation, the eggs are laid in the water and the larvae hatch around three days later. There are four larval instars (L_1, L_2, L_3 and L_4) before they become pupae. Next, the metamorphosis for the aerial reproductive stage (the adult mosquitoes) occurs [13, 24].

Under the stimulus of the need for new methods to combat the arboviruses, vaccines were developed [25]. In Brazil, the development and licencing of the Qdenga vaccine were approved by the *Agência Nacional de VigilânciaSanitária* (ANVISA); This vaccine covers the four-dengue virus serotypes and has a better regulated vaccination schedule when compared to its predecessors [21, 26-28]. However, the distribution of the Qdenga vaccine in the *Sistema Único de Saúde* of Brazil (SUS) still depends on public authorities, and it remains only considered a remedial alternative. AlthoughLA1553, the only chikungunya vaccine candidate worldwide, has been developed, the process for its regulation is still in course. In addition, there are no approved vaccines against Zika virus to date, and even with an efficient vaccine for immunization against yellow fever, its periodically reemerging is recorded. Together, these facts point to need to keep the density of *Ae. aegypti* populations are controlled.

4. ECONOMIC IMPACTS OF *NASUTITERMES CORNIGER* AND *SITOPHILUS ZEAMAIS*

Some insects are used to generate marketable products, such as the case of the silkworm *Bombyx mori* Lin. (Lepidoptera, Bombycidae) whose cocoons are used in the manufacture of biofibers by the textile industry; This structure is the site where the transition between the caterpillar and the pupa phases occurs [29].The African bees *Apis mellifera* L. (Hymenoptera, Apidae) are widely used in apiaries in Brazil for honey production. Beekeeping gained space in the international market, increasing the economic impact of Brazilian products until 2010. In this sense, beekeeping generates employment and income throughout the country, but mainly in the northeast region [30].

On the other hand, there are many insects whose economic impact is negative. For example, termites of the species *Nasutitermescorniger*Motsch. (Blattodea, Termitidae), have a high damaging potential to the sapwood of trees, wooden structures in urban buildings, books, clothes, papers, and furniture. These insects adapt well outside their natural environment and are highly resilient to current control methods [31, 32].*N.corniger*ir part of the deadwood decomposer community due to its ability to digest cellulose. They build their colonies on trees, roots or on the ground and have division of labor and an organized system of castes that comprise a reproductive group restricted to one or few queens, the soldiers (Figure 1B) who defend the colony when there is a sign of invaders, the infertile workers (Figure 1C) who have the function of feeding the reproducers, and the immature forms. The non-reproductive castes have very evident morphological characteristics, such as workers and soldiers who have a well-developed structure with a pointed shape on their heads that gives them the name “Nasutos” [33].

Insects can be considered agricultural pests when they consume a large part of production, making them unsuitable for distribution and commercialization [34, 35]. The damage caused by the insect activity in crops exceeds competition for food and may include the transmission of pathogens to crop plants. It is the case of the aphid species *Aphis gossypii* Glover (Hemiptera, Aphidida), a cotton pest that can transmit a set of disease-causing viruses to crops, including anthocyanosis [36, 37].

Insects of the *Sitophilus* (Coleoptera, Curculionidae) genus are important stored grain pests that attack maize grains and processed foods (cookies, crackers, pasta). They account for severe agricultural losses in developing countries, which may comprise approximately 30% of production, since they reduce the weight of the grain through direct consumption, decreasing their quality, nutritional value, and the germinative potential of seeds [35, 38-40].*S.zeamais*(Figure 1D), the maize weevil, not only feeds on corn kernels but also reproduces and oviposit within them [41]. Its biological cycle includes the egg, larva, pupa, and adult phases and lasts an average of 34 days. The larvae develop within the grains and at the end of development, the adults emerge with a rostrum projected in front of the head, which serves as sexual dimorphism [39]. The projection of males is short and thick and that of females is longer and slender; both are dark brown in color with small spots on the elytra. Each female can oviposit approximately 280 eggs and the oviposition period last about 100 days. The incubation of eggs can oscillate between 3 and 6 days until the hatching of the larvae, which have a yellowish color and darker at the head. The pupae are whitish in color [42].

5. CHEMICAL CONTROL OF INSECT PESTS

Because of the damages caused by the insect pests, humans developed methods to control their populations. One of the widely applied methods is the use of pesticides, toxic chemicals for pest management [2]. However, this kind of substance has low specificity and can be responsible for causing physiological disorders on the people who apply the products or the ones that are nearby the application sites [3]. Furthermore, the hazardous pesticides can linger in the environment and be transported to lakes, rivers, and seas by leaching process, causing a series of impacts for the organisms that live there [43].

The synthetical pesticides are classified based on their chemical composition in organochlorine, organophosphate, carbamates, pyrethroids and neonicotinoids (Table 2). These products have neuroactivity, inhibiting neurotransmitters and voltage dependent channels. Nevertheless, the effects of synthetic insecticides do not affect only insects once neurotransmitters and voltage dependent channels structures are preserved in humans and other mammals [44].

Table 2. Synthetic insecticides and their respective mechanisms of action.

Class of insecticides	**Example**	**Mechanism of action**
Organochlorines	Dichlorodiphenyltrichloroethane (DDT)	Act on voltage dependent ion channels keeping them continuously open leading to an imbalance of cell homeostasis.
Organophosphates	Temephos Malathion Pirimiphos-Methyl Fenitrothion	Inhibition of acetylcholinesterase (AChE), accumulating acetylcholine at synaptic junctions.
Carbamates	Propoxur Bendiocarb	Reversible inhibition of AChE through carbamylation.
Pyrethroids	Deltametrhin Lambda-Cyhalothrin Cypermethrin Cyfluthrin Permethrin	Prevents the closure of sodium channels at the neurons membrane.

References: Stine and Brown [45]; Soderlund e Bloomquist [46]; Larini [47].

Since the start of large-scale use of synthetic pesticides, the incidence of diseases associated with neural and muscular problems has risen. The clinical conditions of Alzheimer's and Parkinson's diseases can be correlated not only with genetic heredity but also with environmental factors such as exposure to hazardous synthetic insecticides. These substances have the potential to dysregulate the dopaminergic pathway, leading to Parkinson's disease, or interfere with acetylcholinesterase activities, which may be associated with Alzheimer's disease [44-49].

Cardiotoxicity is an issue that also could be related with synthetic insecticides. They can induce toxicity in heart tissue through their already known mechanisms. The inhibition of proteases, such as acetylcholinesterase or mitochondrial chain proteins (Table 2), and dysregulation on the balance of the voltage-dependent channels, as occurs in organochlorine poisoning (Table 2), can lead to some metabolic disorders such oxidative stress and apoptosis of myocardial cells, expressed as myocardial infarcts, impaired heart rate and hemorrhage [8, 50, 51].

It is also known that the presence of pesticides in the environment can be hazardous to the organisms living there. After administration of insecticides, toxic substance residues can be leached into aquatic environments. Once there, this substance can be ingested or absorbed by various organisms, such as fish, mussels, and crustaceans, resulting in ecological impacts [52]. Assays using *Danio rerio* (zebrafish) may help to elucidate the effects of pesticides in aquatic systems, which may include hatch delay, cardiotoxicity oxidative stress, and embryo malformations; The ecotoxicity investigations can help to predict the impact of pesticides in aquatic environments, which may result in high vulnerability of aquatic organisms to predation or inefficiency in competing for food or space [52-54].

Indirect impacts can be observed through the accumulation of toxic substances in the body of aquatic organisms. When toxic molecules are available in the environment, they can be absorbed and accumulated by the organisms, such as bivalves, and travel up the food chain, affecting animals at the top [55]. The analysis conducted in the Mondego River estuary of Portugal revealed that a significant portion of the edible species with economic importance were contaminated with pesticide residues. This contamination poses a serious risk to human health, as these pesticides can accumulate in the species that are consumed as food [4].

Despite the environmental and ecological damages, the use of pesticides has represented, for large food producers, one of the most effective strategies in reducing the losses derived from the attacks of pests [2]. In this sense, the search for environmentally safer compounds, a higher degree of biodegradability and less potential for bioaccumulation has motivated scientists in the field of natural products [10, 11].

6. PLANT COMPOUNDS WITH INSECTICIDAL ACTIVITY

An alternative for pest control, less hazardous for human and environment, lies in plant products. Proteins and secondary metabolites from plants are considered promising substances with biological applications, including insecticidal activity. Thereby, researchers look mainly into plants with ethnopharmacological use, as they have a great chemical potential to achieve a desired biological effect [10].

Plant based insecticides use chemical compounds produced by plants for their own protection against insects. These molecules are part of plant metabolism that can be primary and secondary. The primary metabolism involves essential molecules to plant survival, such as carbohydrates, lipids, proteins, and nucleic acids [56]. While the secondary metabolism comprises substances produced in small quantities that may vary between taxonomic groups or due seasonality and stress conditions. Alkaloids, phenolic compounds and terpenoids are secondary metabolites with interesting biological activities, which are generally complex structures under low molecular weight [57]. The distinct patterns of secondary metabolite production are valuable aid plant taxonomy [58].

The insecticidal effects of secondary metabolites may include physiologic changes in organisms, hindering nutrition, preventing the sexual maturation and reproduction processes, compromising embryonic development, and causing malformations [59]. Souza et al. [60] carried out tests with essential oils from two species of *Alpinia sp.* (Zingiberaceae), to investigate the insecticidal and repellent effects against *Rhodniusnasutus*Stål, a vector of Chagas disease. The study indicated the insecticidal potential of essential oils from *Alpinia zerumbet* (Pers.) Burtt et Smith and *Alpiniavittata*W.Bull that caused mortality of 73.3% and 83.3% for *R. nasutus*, respectively, under a concentration of 125 µg/µL. The authors identified a high concentration of terpinen-4-ol in the essential oil of *A. zerumbet*, while that of *A. vittata* had β-pinene as a main compound. In addition, a mortality rate of 100% was recorded when *R. nasutus* were exposed to terpinen-4-ol (25 µg/µL) and β-pinene (44 µg/µL).

Monoterpenes are examples of secondary metabolites with insecticidal activity against *Ae. aegypti*. Silvaet al.[61] assessed the efficacy of *Aristolochiatrilobata*L.monoterpenes against females and larvae of *Ae. aegypti* susceptible or resistant to pyrethroids. The results showed that the monoterpenes were lethal for adult females and had sublethal effects on larvae that can make it more susceptible to predation and incapable to compete for food. The saline extract of *Schinusterebinthifolia*Raddileaves containing flavonoids exerts strong deterrent effect to *S. zeamais* and caused inhibition of proteolytic activity at its midgut, leading to antinutritive effects [62]. Flavonoids can also induce deterrence to *N. corniger* or exert toxicity killing the termites [63].

Some proteins are expressed by plants to defend themselves against insect pests or predators and this ability resulted from a coevolution process. Protease inhibitors and lectins (carbohydrate binding proteins) can act as defense proteins and have their expression modulated by attack by pests and pathogens [64]. Protease inhibitors are mainly present in seeds and tubers with competitive dynamics against protein substrates. Since trypsin is a protease ubiquitously distributed in insects, trypsin inhibitors may have insecticidal activity by causing nutrition disorders and death from starvation [65].

Flowersof *Moringa oleifera* Lam. (Moringaceae) contain proteins with trypsin inhibitor activity that kills *N. corniger* workers [66]; The author showed that the protein-rich preparation of *M. oleifera* flowers was able to inhibit *in vitro* the trypsin-like activity and the growth of microbiota from workers midgut. A *M. oleifera* flower extract containing triterpene, sterol, flavonoids, and a proteinaceous trypsin inhibitor named MoFTI killed *Ae. aegypti* L_2, L_3 and L_4 (LC_{50} of 1.72%, 1.67%, and 0.92%, respectively). The authors showed by a In vivo assay that L4 gut trypsin treated with the extract at CL50 was strongly inhibited (98.6%) after 310 min; Also, the heating of the extract (100° C; 12 h) resulted in loss of trypsin inhibitor and larvicidal activities, indicating indicating a correlation between these effects [67]. When isolated, MoFTI killed *Ae. aegypti* newly hatchedlarvae and causeddelay of development; The inhibition of L4 midgut microbiota growth by MoFTI (minimum inhibitory concentration of 0.031 mg/mL) was also demonstrated [67]. Protease inhibitor from *Allium sativum* L.delayed the development and caused death of *Ae. aegypti* larvae [68].

Lectins are proteins that bind carbohydrates in a reversible and specific way, these either being free, conjugated or part of the cell surface. Researchers report lectins as a healing, immunomodulators, antibacterial, antifungals, antivirals, and insecticidal agents [69]. The toxicity of lectins is described to different insect orders such as Lepidoptera, Coleoptera and Hemiptera. The affinity for carbohydrates allows these proteins to associate with glycoproteins or other glycoside structures in the insect body causing harmful effects on fertility, nutrition, development, and survival because of physiological disorders [70]. Lectins from *M. oleifera* seeds showed larvicidal effects on *Ae. aegypti* associated with dysregulation of digestive enzymes, as well as harmed the viability of eggs and acted as a chemical cue for oviposition[71].

The lectin from *Opuntiaficus-indica*(L.) Mill.cladode caused weight reduction of *S. zeamais* [33]; The authors attributed this effect to the lectin's ability to interfere with the digestion and absorption of nutrients, making it difficult to convert food into biomass. Lectins from bark, heartwood, and leaves of *Myracrodruonurundeuva*Fr. All. resisted to incubation with proteases from *N. corniger* gut and kiled Soldiers and workers, as well as showed *in vitro* antimicrobial activity on microbiota from their guts [72].

7. BIBLIOMETRIC APPROACH

Bibliometric analysis was used here as a tool to identify trends in the field of plant-based insecticides and guide new research toward less explored avenues or highlight topics that have become less relevant [73]. Although systematic reviews and meta-analyses are quite efficient in conducting qualitative and quantitative assessments, bibliometric analysis can simultaneously perform both types of evaluations using information such as authorship, publication countries and keyword occurrences [74].

Our search revealed a total of 363 published manuscripts, being reduced to 236 original papers after applying the exclusion criteria. Figure 2 represents the number of original articles reporting the production and evaluations of plant-based insecticides published between 1991 and 2023. The data shows that the topic gained prominence from the 2000s onwards, with a strong expansion from 2010, and a peak of production in 2021, with 25 publications, which has not been surpassed to date.

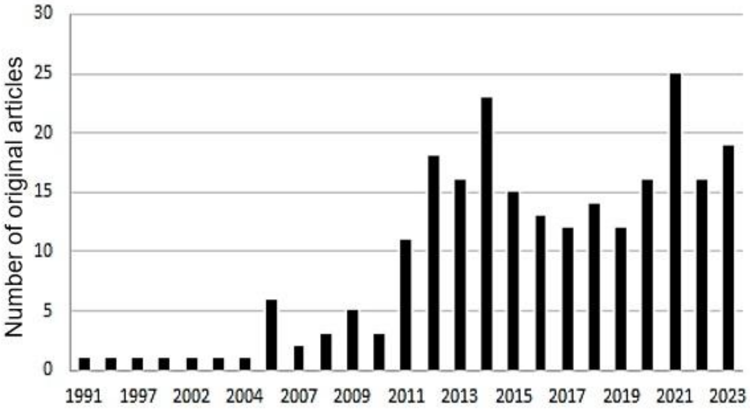

Figure 2. Number of original article publications by year in the field of plant-based insecticides. Data collection used the keywords: “Plant Extract”; “Insecticide Activity”; “*Sitophilus zeamais*”; “*Nasutitermescorniger*”; “*Aedes aegypti*” in the database Web of Science. Studies that did not use plant compounds, did not evaluate insecticidal activity, did not target the species *S. zeamais*, *N. corniger* or *Ae. aegypti*, as well as review works were excluded

The analysis of the data from the manuscripts using the *Vosviewer*software allowed identify co-authorship and keyword co-occurrence. When analyzing co-authorship among researchers, restricting the results to those with a minimum of 3 publications in the field, it was identified that 57 authors met this criterion, maintaining a significant network of collaboration among themselves, with few dispersion regions (Figure 3A).

It was found a predominance of authors in countries of tropical regions; Forty-seven countries with publications in the area were identified, with the key studies being developed in India (88 documents, 34.4%) and Brazil (56 documents, 21.9%) (Figure 3A). Additionally, the countries with the highest number of publications maintain a stronger co-authorship relationship (Figure 3B); They are predominantly countries in Asia (India, Thailand, Taiwan, Saudi Arabia, Malaysia, United Arab Emirates), Latin America (Brazil, Mexico, Ecuador), and a few countries from the African and European continents (Nigeria, Yemen, Egypt, Tanzania, England, Italy).

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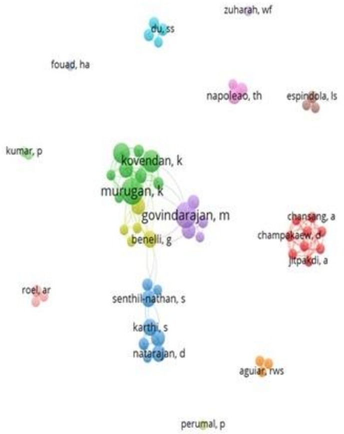
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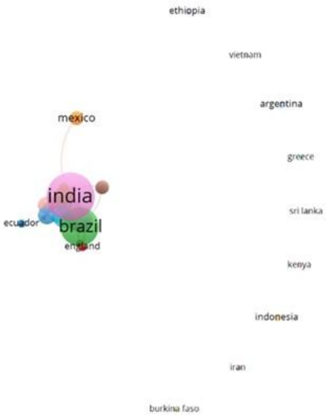
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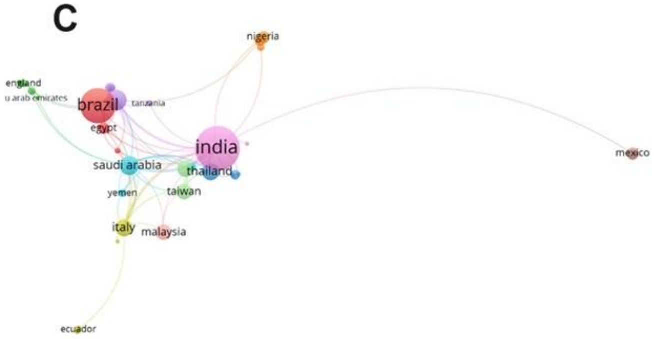
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Figure 3. Overview of co-authorship network of researchers in the field of plant-based insecticides (A). Source: Web of Science Core Collection). Overview of co-authorship patterns among countries (B and C) (CLARIVATE, 2023)

This pattern of distribution of the publications may be attributed to the growing interest of tropical countries in controlling insect pests, particularly of disease vectors including the dengue, chikungunya, zika, and yellow fever [75]. These arboviruses have become increasingly concerning in recent years, due to the climate changes and the high population growth [76].

Interesting, Brazil had a good amount of publication numbers between the years 2015 and 2020 (Figure 4). This period corresponded to an epidemy of chikungunya and zika associated with microcephaly specially in the region northeast of Brazil [77-79]. In this sense, the increased interest in alternatives to control *Ae. Aegypti* population may be linked to this epidemic.

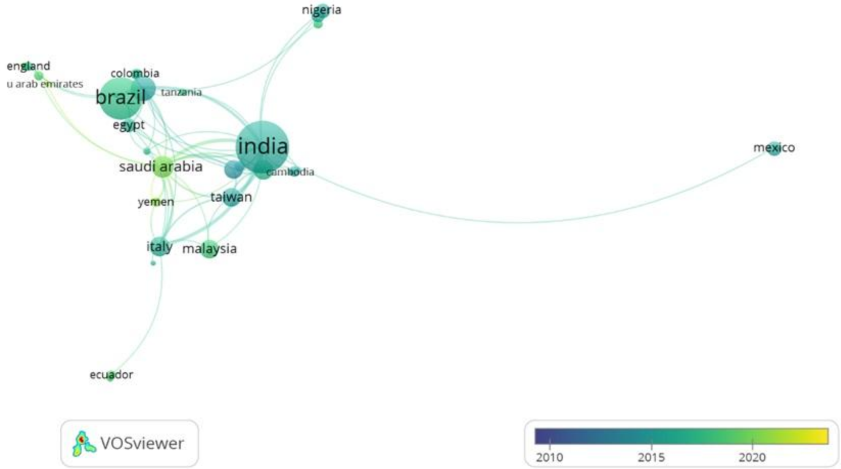

Figure 4. Overview of co-authorship patterns among countries in the field of plant-based insecticides (CLARIVATE, 2023).

The keyword co-occurrence analysis reinforced the pattern of regions that publish the most in this field of study. After restricting the keywords to that present in at least 5 documents, a total of 53 keywords were selected, and the analysis showed that the main pillars of the studies were "essential oils," "larvicidal activity," and "*Aedes aegypti*" (Figure 5). The prevalence of *Ae. aegypti* and the mosquito-borne diseases in the tropical countries may explain the distribution patterns of literature production reported here.

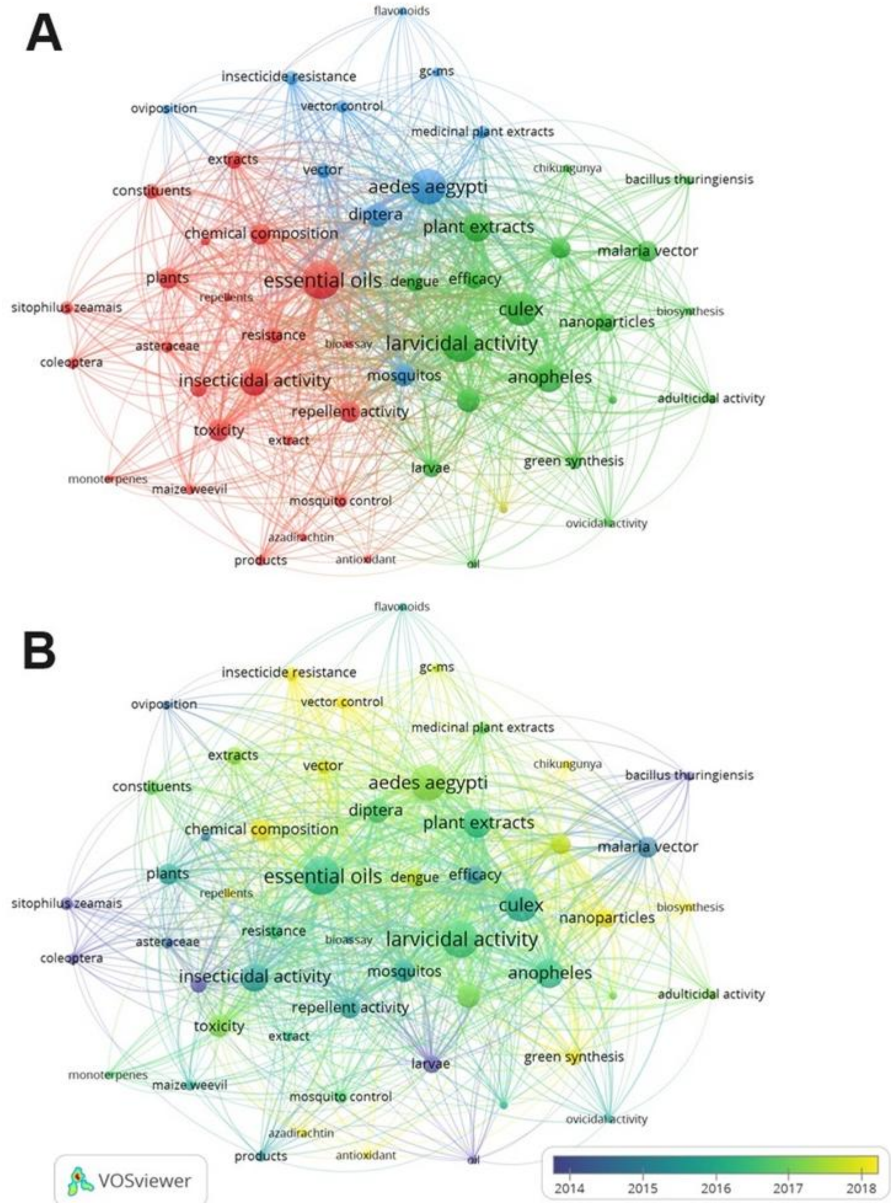

Figure 5. Keyword co-occurrence analysis of terms mentioned in at least 5 publications (A) Keyword co-occurrence analysis of terms mentioned in at least 5 publications (A) and overlay representation (B) in the field of plant-based insecticides and overlay representation (B). Source: Web of Science Core Collection (Clarivate, 2023)

The *Vosviewer*platform also offers an additional visualization mode called 'Overlay', where the nodes related to keywords were distinctly colored according to the publication year of the articles in which they are mentioned. This method enables the identification of keywords most frequently used over the publication period in the field, through color variation, providing a basis for inferences about current topics and potential research trends within the subject area.

When viewing the keyword co-occurrence analysis through the 'Overlay' representation, it becomes evident that terms like "larvae" and "oil" are the most traditionally cited, highlighting that the larvicidal activity of essential oils has historically been one of the primaries focuses of research related to plant-based insecticides (Figure 5).

Although most of the selected documents focus on evaluating the larvicidal potential of essential oils and plant extracts, the terms “biosynthesis”, “vector control” and “nanoparticles” were also detected which appear yellow, indicating that they are predominantly present in more recent publications.

In our bibliometric approach, the green synthesis of metallic nanoparticles appears as a strong trend on the topic, probably because it increases the action of chemicals and reduces non-target toxicity compared to free components [80]. It has been well reported that the use of plant extracts in the synthesis of silver nanoparticles can be highly efficient in reducing ions, which combined with their complex composition, generally rich in secondary metabolites and classes of proteins with insecticidal potential, can represent an efficient pest control strategy [80].

Silver nanoparticles synthesized from the methanolic extract of the leaves of *Passiflorafoetida* L. (Passifloraceae) killed different larval intars and pupae of *Ae. aegypti* with LC_{50} ranging from 47.8 ppm to 88.4 ppm [81]. Furthermore, iron oxide nanoparticles containing the aqueous extract of *Grevillea robusta* A. Cunn. ex R.Br. (Proteaceae) leaves killed L2 and L4 of *Ae. aegypti*, with LC_{50} of 238.05 and 259.07 ppm, respectively [82]. These data represent important advances in nanotechnology based on natural products.

4. CONCLUSION

Compounds and molecules isolated from plants have a wide potential for the development of biotechnological products for control insect populations considered as urban or crop pests. Currently, many studies point to protease inhibitors, lectins, and secondary metabolites as promising insecticides. Furthermore, many studies focus on the insecticidal activity against *Ae. aegypti* and other mosquitoes species more than *S. zeamais* or *N.corniger*, indicating that there is room for more research with these two species. The bibliometric approach revealed a growing interest in silver nanoparticles in recent years, which could become a starting point for widely marketable product formulations. Therefore, the topic is current and relevant, especially in tropical and agriculturally developed regions worldwide. However, more studies are still needed on the applicability of formulations and side effects against non-target organisms.

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