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Advances in botanical-based nanoformulations for sustainable cotton insect pest management in developing countries

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Cotton is an important crop that significantly contributes to the economies of developing countries, providing income for farmers and driving economic growth in rural areas. However, cotton production in developing countries faces significant challenges due to insect pest infestations. The main impacts include yield losses and increased reliance on synthetic pesticides. Recent advances in pest management are constrained by the use of chemical pesticides that are harmful to the environment and less efficacy and stability of bio-based formulations, especially plant-based. Challenges are more significant in the developing countries where low technology, and reliance on synthetic adulterated products are experienced. To evaluate advances in sustainable pest management, 760 articles were collated and screened. A total of 39 qualified peer-reviewed articles were used to evaluate current research advancements in botanical nanoformulations for sustainable cotton insect pest management in developing countries and examined their efficacy on key cotton insect pests, formulation techniques, mode of action and environmental impact while identifying challenges such as nanoparticle stability and scalability. Results showed that botanical nanoformulations such as silver and zinc nanoparticles, nano-emulsions, and polymeric carriers enhance efficacy, stability, and environmental sustainability. About 85% of the studies were laboratory-based experiments, with only 15% being semi-field and/or field trials. Findings indicate that botanical nanoformulations are viable alternative for manging cotton insect pest management. However more researches are needed to optimize their stability and efficacy in real-world cotton insect pest management in developing countries context.

KEYWORDS

botanical, nanoformulations, pesticidal plant extracts, sustainable cotton insect pest management, eco-friendly nanopesticides, metal nanocarriers, polymeric nanocarriers

1 Introduction

Cotton, *Gossypium hirsutum* L., is an important crop in many developing countries, serving as a critical source of income and livelihood for farmers (Malinga, 2021; Soumaré et al., 2021). Globally, in 2014, cotton generated $600 billion, from 25.6 million tons of lint harvested from 32 million hectares (Ateeq-ur-Rehman et al., 2020; Malinga, 2021). By 2018, cotton was cultivated in over 64 countries whereby India, United States, China, Brazil, and Pakistan produced over 75%, with India and China contributing 50% (Malinga, 2021). Other major producing countries include Australia, Uzbekistan, Turkey, Turkmenistan, Egypt and Burkina Faso, all of which play crucial roles in the global cotton market (Ateeq-ur-Rehman et al., 2020; Khawar and Singh, 2020). Africa contributes to 15% of lint exports, generating $2.1 billion in 2019.Cotton in West and Central Africa (WCA), where it is a significant economic driver, contributing between 3% and 15% to the gross domestic product (GDP) (Malinga, 2021; Soumaré et al., 2021).

Despite its economic significance, cotton production in developing countries faces substantial challenges, with pest infestations causing annual yield losses exceeding 50% in Africa and Asia (Sharma et al., 2017; Overton et al., 2021; Raju and Sharma, 2021; Ratto et al., 2022; Devi et al., 2023) (Overton et al., 2021; Ratto et al., 2022; Devi et al., 2023) (Sharma et al., 2017; Raju and Sharma, 2021). Cotton is susceptible to a wide range of insect pests which causes substantial damage to yield if left uncontrolled (Riaz et al., 2021), these insets include *Helicoverpa armigera* (Hubner), *Earias insulana* (Boisdual), *E. vitella* (Fabricius), *Pectinophora gossypiella* (Saunders), *Spodoptera frugiperda* (J. E. Smith), *Spodoptera exigua* (Hübner), *Spodoptera littoralis* (Boisd.), *Amrasca biguttula* (Ishida)/*Amrasca devastans*, *Aphis gossypii* (Glover), *Thrips tabaci* (Lind), *Tetranychus cinnabarinus*, *Phenacoccus solenopsis* and *Bemisia tabaci*.

A commonly used insect pest management option in developing countries is the application of chemical pesticides (Siddiqua et al., 2016; Akhter et al., 2023; Saini and Gupta, 2024). Despite their quick action and efficiency in the management of pests, chemical pesticides are reported to be unsustainable, create insect resurgence (Shahid et al., 2021), cause insect resistance to insecticides (Devi et al., 2014; Shahid et al., 2021; Kumar Sharma et al., 2022), kill natural enemies of insect pests and are often too expensive for smallholder farmers (Khanra et al., 2018; Nursal, 2019; Abdelaal et al., 2021). Chemical pesticides are also evidenced to have environmental contamination impacts (Sharma et al., 2020; Sarker et al., 2021). Additionally, most of the chemical pesticide applications are ineffectively or wrongly applied resulting in the loss of more than 70% of the given dose (Hou et al., 2021). In developing countries, smallholder farmers lack access to protective gear (Aïhounton et al., 2021) a scenario that exposes them to harmful pesticides (Overton et al., 2021; Soumaré et al., 2021). As a result, there is a pressing need for alternative pest management strategies that are effective, eco-friendly and sustainable (Isman, 2019; Acheuk et al., 2022; Srinivasan et al., 2022).

Botanical plant extracts containing protective secondary metabolites can effectively manage insect pests in storage and field conditions (Karani et al., 2017; Mkindi et al., 2019; Mkindi et al., 2020). They are made of biodegradable organic materials, have diverse bioactivity, and have low toxicity to non-target organisms (Bharani and Namasivayam, 2017; Prema et al., 2018). Some botanical formulations are contact, respiratory or stomach poisons (Sarwar and Sattar, 2016; Sarwar, 2017; Sarwar, 2023). They may also work as repellents. antifeedants or as phenological inhibitors (Sarwar and Sattar, 2016; Sarwar, 2023). However, the use of botanical pesticides is limited by physical stability, quick environmental degradation and poor water solubility (Abdelaal et al., 2021; Bae et al., 2022). Botanical nanoformulations have emerged as promising avenues to improve the efficacy, stability, solubility targeted and controlled release of these bioactive compounds against cotton insect pests (Khanra et al., 2018; Abdelaal et al., 2021; Metwally et al., 2022; Rafea et al., 2022; Alfaro-Corres et al., 2023). Botanical nanoformulations are defined as the process of creating nanoscale formulations derived from pesticidal plant materials for various applications with particular on cotton insect pests. Nanoformulations emerged from several processes including biogenic/biological synthesis, green synthesis, chemical synthesis, polymeric nanoparticles synthesis and nanoemulsions (Anees et al., 2022; Devi et al., 2023; Khaleel et al., 2023). Many different matrices can be used to produce nanostructured systems, including biodegradable polymers (Wani and Ali Khan, 2016; Sakban-Al-Tamimi et al., 2020; Anees et al., 2022; Qarachal et al., 2024), active compounds isolated from plants, metallic oxides as well as the essential oils (EOs) (de Oliveira et al., 2018). This paper aims to provide an overview of the use of botanical nanoformulations in cotton insect pest management in developing countries, focusing on the current research and advancements in development, enhancement of botanical efficacy, mode of action and challenges of botanical nanoformulations for cotton pest management in developing countries.

2 Methodology

2.1 Search strategy

This review aimed to answer critical questions regarding the evidence of botanical nanoformulations in cotton insect pest management and their comparative effectiveness against conventional methods in terms of efficacy, mode of action, and implementation challenges in developing countries. The study employed the Population, Intervention, Comparison, and Outcome (PICO) framework to refine the search criteria for identifying relevant studies. Population (P): Cotton insect pests in developing countries, Intervention (I): Botanical nanoformulations for pest management, Comparison (C): Conventional insecticides and non-nano botanical insecticides, Outcome (O): Effectiveness of nanoformulations in controlling cotton insect pests. A structured literature search was conducted in Google Scholar and Scopus databases. These platforms were selected due to their extensive repositories of peer-reviewed articles and accessibility through the Nelson Mandela African Institution of Science and Technology. The search string consisted of major keywords and their related terms, including “Botanical nanoformulations,” “Cotton insect pests,” and “Pest management” within developing countries. The full search string is detailed in Table 1.

TABLE 1 Literature search string and source.

Database	Search String	Result	Time frame
Google Scholar 13 Oct 2024	"Botanical based nano pesticides" OR "plant-based nano pesticides" OR "botanical nanoparticles" OR "botanical insecticides" OR "plant-based nano-formulations" OR "plant base nano pesticides" OR "botanical-based nanoformulations" OR "plant nano emulsion" OR "plant nano encapsulation" OR "biopesticide" OR "plant-based carriers" OR "Botanical nanoparticle formulations" OR "Nano-formulated botanical extracts" OR "microcarrier formulations" OR "Nanoparticle formulations" OR "Nano-encapsulated formulations" OR "plant-derived nanoparticles" OR "herbal nanoparticles" OR "natural plant extracts" OR "nanoparticles" OR "Nano-encapsulated pesticides" OR "Nanotechnology-based pesticides" OR "nanoparticle size" OR "nano-composites" OR "nanocases" OR "emulsification" AND "Cotton insect pests" OR "Cotton Insects" OR "Cotton insect threats" OR "Cotton insect infestations" OR "Cotton agricultural pests" OR "Cotton insect nuisances" OR "African Cotton bollworms" OR "*Helicoverpa armigera*" OR "H. armigera" OR "Cotton Bollworm" OR "*Spodoptera frugiperda*" OR "*Spodoptera littoralis*" OR "thrips" OR "*Thrips tabaci*" OR "cotton jassid" OR "Aphids" OR "*aphis gossypii*" OR "Mealybugs" AND "Management" OR "manage" OR "Control" OR "suppress" OR "eradicated" OR "eradicate" OR "regulation" OR "regulate" OR "mitigation" OR "Integrated pest Management" AND PUBYEAR > 2013 AND PUBYEAR < 2025	19	2014-2024
Scopus 13 Oct 2024	"Botanical based nano pesticides" OR "plant-based nano pesticides" OR "botanical nanoparticles" OR "botanical insecticides" OR "plant-based nano-formulations" OR "plant base nano pesticides" OR "botanical-base nano formulation" OR "plant nano emulsion" OR "plant nano encapsulation" OR "biopesticide" OR "plant-based carriers" OR "Botanical nanoparticle formulations" OR "Nano-formulated botanical extracts" OR "microcarrier formulations" OR "Nanoparticle formulations" OR "Nano-encapsulated formulations" OR "plant-derived nanoparticles" OR "herbal nanoparticles" OR "natural plant extracts" OR "nanoparticles" OR "Nano-encapsulated pesticides" OR "Nanotechnology-based pesticides" OR "nanoparticle size" OR "nano-composites" OR "nanocases" OR "emulsification" AND "Cotton insect pests in developing countries" OR "Cotton Insects" OR "Cotton insect threats" OR "Cotton insect infestations" OR "Cotton agricultural pests" OR "Cotton insect nuisances" OR "African Cotton bollworms" OR "*Helicoverpa armigera*" OR "H. armigera" OR "Cotton Bollworm" OR "*Spodoptera frugiperda*" OR "*Spodoptera littoralis*" OR "thrips" OR "*Thrips tabaci*" OR "cotton jassid" OR "Aphids" OR "*aphis gossypii*" OR "Mealybugs" AND "Management" OR "manage" OR "Control" OR "suppress" OR "eradicated" OR "eradicate" OR "regulation" OR "regulate" OR "mitigation" OR "Integrated pest Management") AND PUBYEAR > 2013 AND PUBYEAR < 2025	741	2014-2024
		760	

2.2 Selection criteria

A systematic filtering approach was used to ensure the inclusion of relevant studies. The inclusion and exclusion criteria (Table 2) were designed to focus on peer-reviewed articles published between 2014 and 2024 in English, while excluding non-relevant and duplicate studies. Screening was performed in three stages. First; title screening, articles were selected based on keywords, research location, and scope. Second; abstract screening, abstracts were reviewed to assess the focus on pest management, formulation techniques, insect pest species, and research outcomes. Third; full-text review, studies were assessed to confirm their relevance to botanical nanoformulations insect pest management in cotton (Figure 1). This review collected data on nanoparticle types, plant species, lethal concentrations (LC_{50} and LC_{90}), modes of action, and environmental effects. Data synthesis was performed using thematic categorization.

2.3 Data extraction and statistic analysis

The data extraction process followed established systematic review guidelines (PRISMA) (Page et al., 2021) capturing key study parameters, including nanomaterials used, nanoparticle synthesis methods, plant species and their derived compounds, targeted insect pests, and efficacy metrics. Relevant bibliographic details, such as author names, publication year, and study location, were also documented in excel sheet for structured analysis. The extracted data were organized to reflect the key theme and synthes relative to research question. Comparative assessment techniques identified the strengths and weaknesses of different formulations. Thematic analysis was also employed to examine trends in synthesis methods, formulation stability, and practical applicability in agricultural settings. The integration of findings allowed for an evidence-based discussion on the feasibility of botanical nanoformulations in sustainable cotton pest management.

2.4 Limitations and bias considerations

Recognizing the predominance of laboratory-based studies 85% over field-based trials (15%), a limitation of this review is the potential overestimation of laboratory-reported efficacy. To mitigate this, studies were categorized based on experimental conditions (e.g., laboratory, semi-field, field) to facilitate a realistic interpretation of findings (Figure 2). Moreover, publication bias was minimized by including studies with both positive and negative results. The use of multiple databases and strict inclusion criteria further helped reduce selection bias.

3 Results

3.1 Overview and scope of evidences

The study mainly focused on articles from developing countries. Overall, India had more reported studies (Riaz et al., 2021), followed

TABLE 2 Inclusion and exclusion criteria based on PICO.

PICO	Inclusion criteria	Exclusion Criteria
Population	Cotton insect pests in developing countries	insect pest in other crops
Intervention	Botanical nano-formulations	Conventional insecticides and non-nano botanical insecticides.
Comparison	Studies comparing nano-formulations with others	Studies without comparative analysis
Outcome	Efficacy and scalability	not related to insect pest management
Other criteria	Study type - Research articles and peer-review articles.	Books, book chapters, Duplicate articles, Government reports,
	Language of publication -English	Not written in English
	Published between 2013 - 2025	Published before 2014

by Egypt and Brazil (six). Other developing countries with research articles included Iran, Côte d'Ivoire, Jordan, Iraq, Saudi Arabia, Indonesia, and Pakistan (Figure 3). The source of articles aligns with the significant role these countries play in global cotton production, with India, Brazil, and Pakistan ranking among the top producers. Egypt and Côte d'Ivoire, known for their high-quality long-staple cotton, contribute significantly to the textile industry, while countries like Iran, Iraq, Saudi Arabia, Jordan, and Indonesia are emerging players in cotton research, textile industry and pest management, Most of the reviewed research articles (85%) reported research conducted under laboratory conditions (Figure 2), where 33 of 39 reviewed articles were laboratory experiments, two were both laboratory and semi-field, one was both laboratory and field, three semi-field and one field experiment. This underlines the importance of optimizing formulation efficacy and collecting foundational data in controlled situations before scaling to more complicated field settings. While laboratory investigations allow for exact variable measurement and early assessment of performance, the limited number of field trials raises questions about the formulations' practical application in a variety of agricultural circumstances. The findings were organized into thematic categories.

3.2 Pesticidal plants used in nanoformulations for insect pest management in cotton

The review identified 45 plant species researched for nanoformulations for management of cotton insect pests, with *Azadirachta indica* most frequently mentioned (12%), followed by *Punica granatum* (5%). *Calotropis procera*, *Origanum vulgare, Piper aduncum, Pongamia pinnata* and *Thymus vulgaris* accounting for 3% each. Other plant species accounted for 2% each onthe reviewed articles as follows; *Acacia catechu, Allium sativum, Annona squamosa, Artemisia herba-alba, Basilicum ocimum, Borago officinalis, Camptotheca acuminata, Capsicum chinense, Citrus limon, Cinnamomum camphora, Cnidium monnieri, Cuminum cyminum, Cymbopogon citratus, C. nardus, Euphorbia hirta, Ficus religiosa, F.benghalensis, Glandora prostrata, Heliotropium indicum, Ipomea carnea, Jatropha curcas, Justicia adhatoda, Lippia multiflora, Matricaria chamomilla, Myrtus communis, Ocimum basilicum, Olea europaea, O. majorana., P. hispidinervum, P. glabra, Phytolacca americana, Rosmarinus officinalis, Ruta graveolens, Sophora flavescens, Tagetes patula, T. daenensis, Ulex europaeus*, and *Zingiber officinaleas.* These plants were reportedly rich in bioactive compounds which enhance nanoparticle efficacy through targeted pest disruption (Figure 4).

The pesticidal plants are predominantly found within the Fabaceae, Lamiaceae, Asteraceae, Rutaceae, Apiaceae, Cucurbitaceae, Piperaceae, Solanaceae, Lythraceae, Caryophyllaceae, Convolvulaceae, Thymaceae, Phytolaccaceae, Rosaceae, Boraginaceae, Annonaceae, and Zingiberaceae plant families (Figure 5). The reviewed articles reveal that pesticidal compounds are found in various plant parts, including leaves, stems, roots, rhizomes, bark, flowers, fruits, cloves, and seeds (Bharani and Namasivayam, 2017; Khanra et al., 2018; Tia et al., 2021).

3.3 Cotton insect pests identified

In the analysis of 39 reviewed articles on cotton pests tested against botanical nanoformulation, the most frequent studied insect was *S. frugiperda* cited in nine articles, followed closely by *H. armigera* cited in eight articles, Aphid species (*A. gossypii, M. euphorbiae, B. brassicae*) in five articles while *S. litura* and *S. littoralis* each appeared in four articles and *P. solenopsis* was referenced in three articles. Other insect pests like *T. urticae* and *B. tabaci* were mentioned in two articles each, while pests such as *E. insulana, P. gossypiella* and *S. exigua* appeared in one article for each (Table 3).

3.4 Nanomaterials and nanoformulation synthesis method

The botanical nanoformulation syntheses methods identified from the reviewed articles were five which include polymeric nanoparticles (30%), biogenic synthesis (25%), green synthesis (20%), chemical precipitation (10%), and nanoemulsification (15%). Polymeric carriers like chitosan and Poly-lactic-co-glycolic acid (PLGA) enhance stability and controlled release, while biogenic and green synthesis employ plant extracts for eco-friendly nanoparticle production. Chemical precipitation ensures precise nanoparticle size control, and nanoemulsification improves solubility and dispersion of essential oils (EOs). Nanomaterials identified from the 39 articles applied in botanical nanoformulations include metal-based nanomaterial such as silver nanoparticles (AgNPs), zinc oxide nanoparticle (ZnONPs), latex-fabricated gold nanoparticles (AuNPs), magnesium oxide nanoparticle (MgONPs) and copper oxide nanoparticles

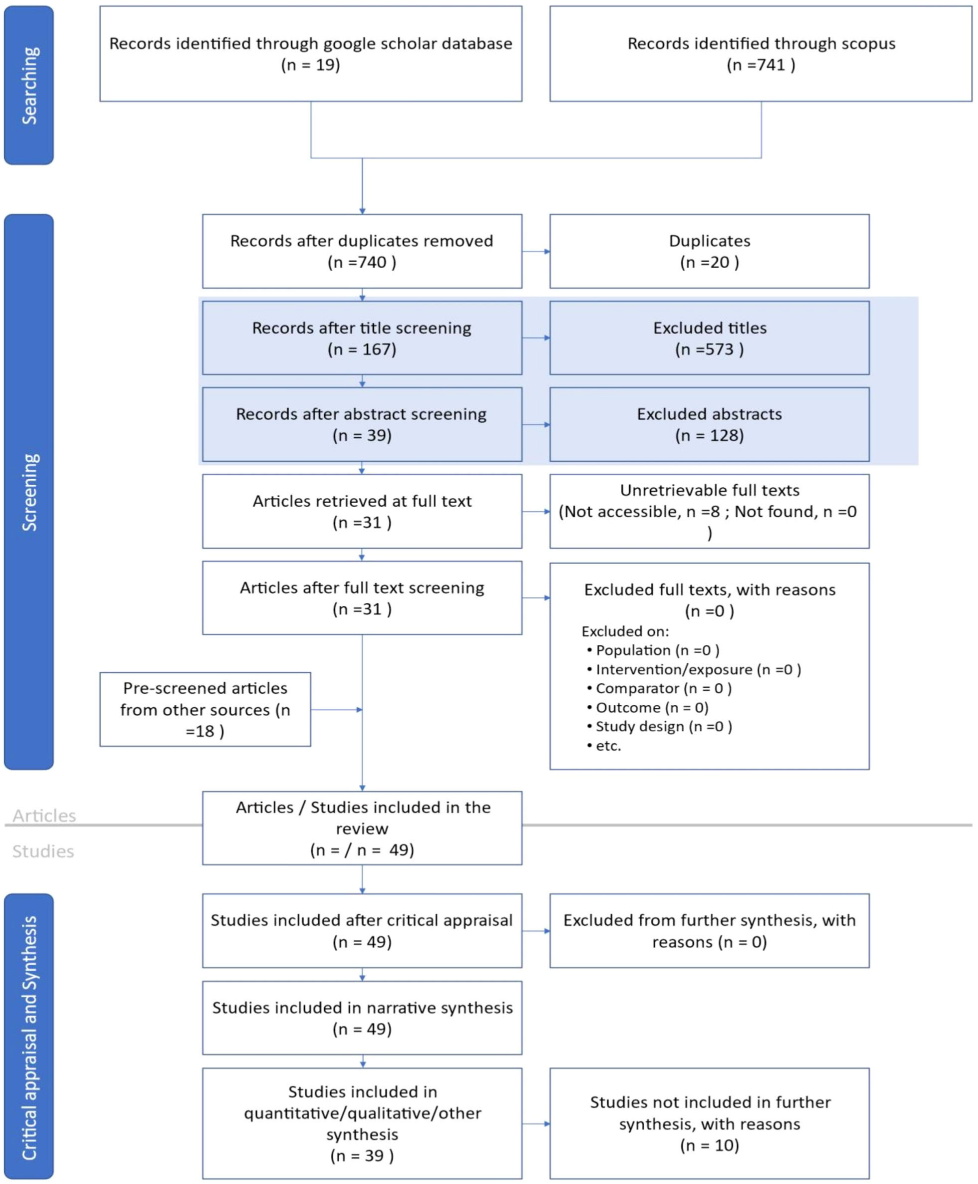

FIGURE 1
ROSES flow diagram for systematic reviews, version 1.0(1). Reproduced from Haddaway et al. (2017), licensed under CC BY 4.0.

(CuONPs) and Polymeric nanomaterials like chitosan nanoparticles (ChNPs) and PLGA. Table 4 summarizes the nanomaterials used in the synthesis of botanical nanoformulations.

3.5 Status of efficacy of botanical nanoformulations against cotton insect pests

3.5.1 Metal-based nanoparticles

Evaluation of botanical nanoformulations from the reviewed articles showed diverse efficacy main reported on lethal concentration. Biosynthesis AgNPs using Oxymatrine had 0.5 ml/L as lethal concentration to kill 50% (LC_{50}) and 1.5 ml/L lethal concentration to kill 90% (LC_{90}) of *A. gossypii*, significantly increasing mortality compared to untreated controls (Sakban-Al-Tamimi et al., 2020). Biogenic AgNPs affected the developmental period of *S. litura* with an LC_{50} of 31.2 µg/mL showing improved efficacy over conventional insecticides (Bharani and Namasivayam, 2017). Silver nanoparticles synthesized from *B. officinalis* showed an LC_{50} of 0.33 mg/g and an LC_{90} of 1.7 mg/g against *S. littoralis* (Hazaa et al., 2021) indicating increased efficacy compared to traditional methods. Silver nanoparticles (*A. indica*) and (*P. pinnata*) against *H. armigera*, exhibited LC_{50} values of 500 ppm and 600 ppm with LC_{90} values reaching 2000 ppm and 1500 ppm respectively (Anees et al., 2022). In comparison, *P. pinnata*-based AgNPs demonstrated slightly higher LC_{50} and LC_{90} values, indicating a marginally reduced insecticidal activity as compared to *A. indica* based AgNPs.

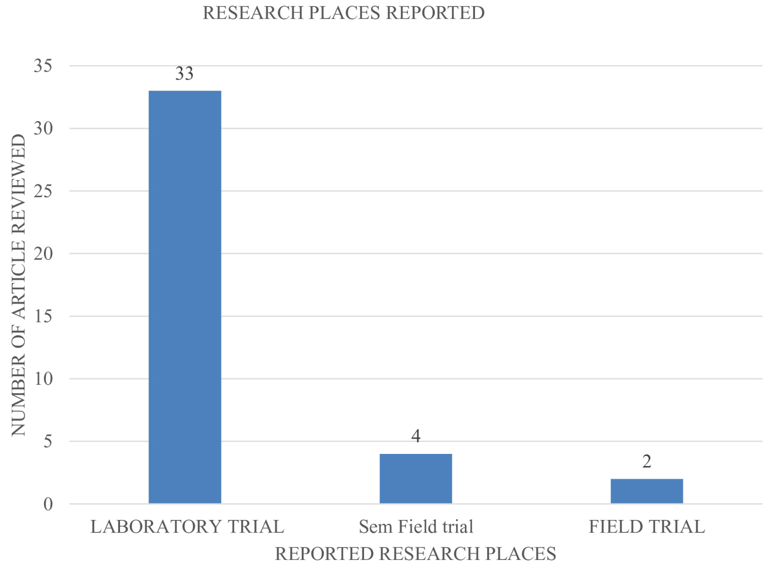

FIGURE 2
Condition in which research was conducted.

Green-synthesized silver nanoparticles from *E. hirta* demonstrated an LC_{50} of 2.905 ppm and an LC_{90} of 9.402 ppm against *H. armigera* (Devi et al., 2014), indicating significantly higher efficacy than conventional treatments. Silver nanoparticles from *A. herba-alba* exhibited LC_{50} values of 74.569 ml/ml (feeding) and 27.47 ml/ml (contact), LC_{90} values were 176.86 ml/ml (feeding) and 203 ml/ml (contact) (El-Ashmouny et al., 2022) signifying increased efficacy. Silver nanoparticles from *A. catechu* reported LC_{50} values of 71.04 mg/mL for *S. litura* and 85.33 mg/mL for *H. armigera*, LC_{90} for *S. litura was* 74.78 mg/mL and *H. armigera was* 88.91 mg/mL showing improved efficacy over traditional insecticides (Baranitharan et al., 2021). Toxicological effects of neem based AgNPs against *H. armigera* showed an LC_{50} of 114.67 ppm and LC_{90} of 202.71ppm (Asghar et al., 2022), indicating increased efficacy compared to standard treatments. Rosemary-AgNPs LC_{50} values for *P. gossypiella* and *E. insulana* were 18.655% and 16.75%, and their LC_{90} values were 143.29% and 64.39%, respectively (Kandil et al., 2024).

Screening of ZnONPs and CuONPs against *S. frugiperda* showed LC_{50} values of 520 ppm (ZnONPs) and 440 ppm (CuONPs) and LC_{90} for ZnONPs was 750 ppm and 500 ppm for CuONPs while neem alone LC_{50} was 500 ppm and LC_{90} was 1000 ppm indicating improved efficacy for nanoformulations (Mohammad et al., 2024). On the other toxicological effect of ZnONPs against *H. armigera* was LC_{50} 127.79 ppm and LC_{90} 242.97 ppm (Asghar et al., 2022).

3.5.2 Polymeric nanomaterials

Efficacy of polymeric nanoparticles were extracxted from the reviewed article and presented below. Nanocapsules loaded with *T. daenensis* EOs exhibited an LC_{50} of 208.28 ppm (nanocapsulated) and 702.57 ppm (raw EOs) and LC_{90} was 1026.44 ppm

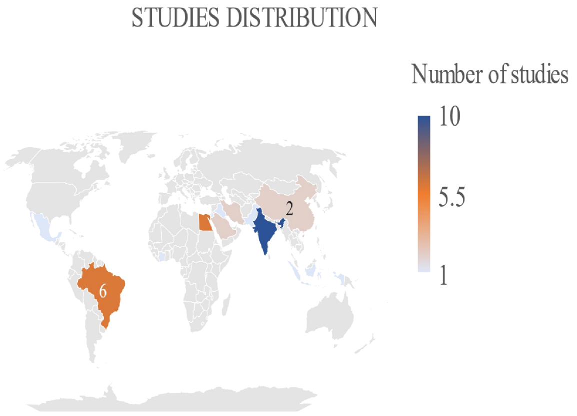

FIGURE 3
Distribution of botanical-based nanoformulations research across developing countries.

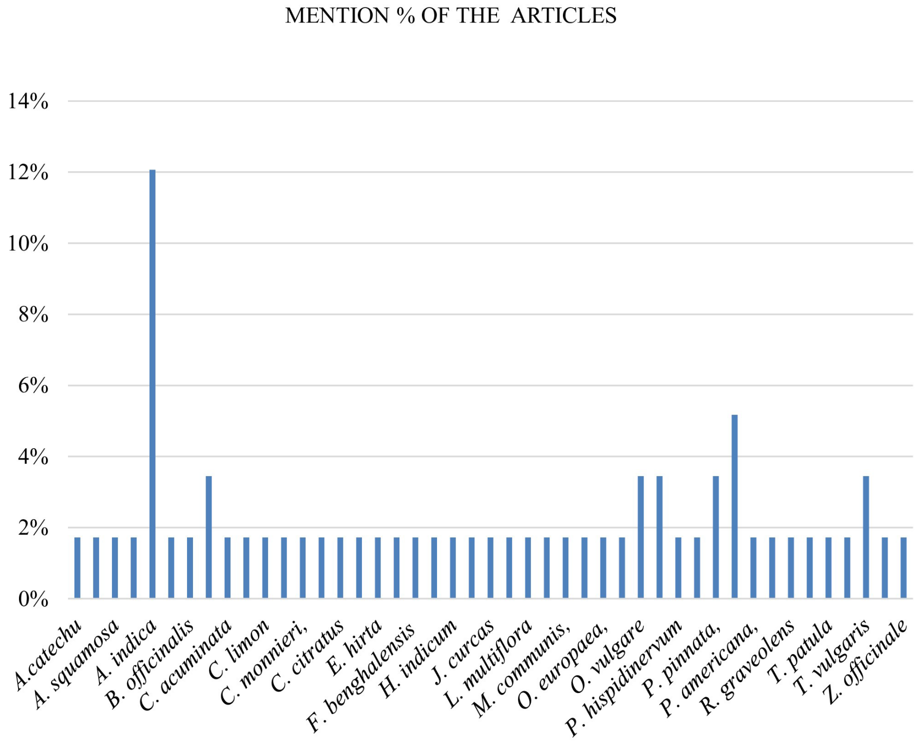

FIGURE 4
Percentage distribution of 45 pesticidal plant species researched for nanoformulations in cotton pest management.

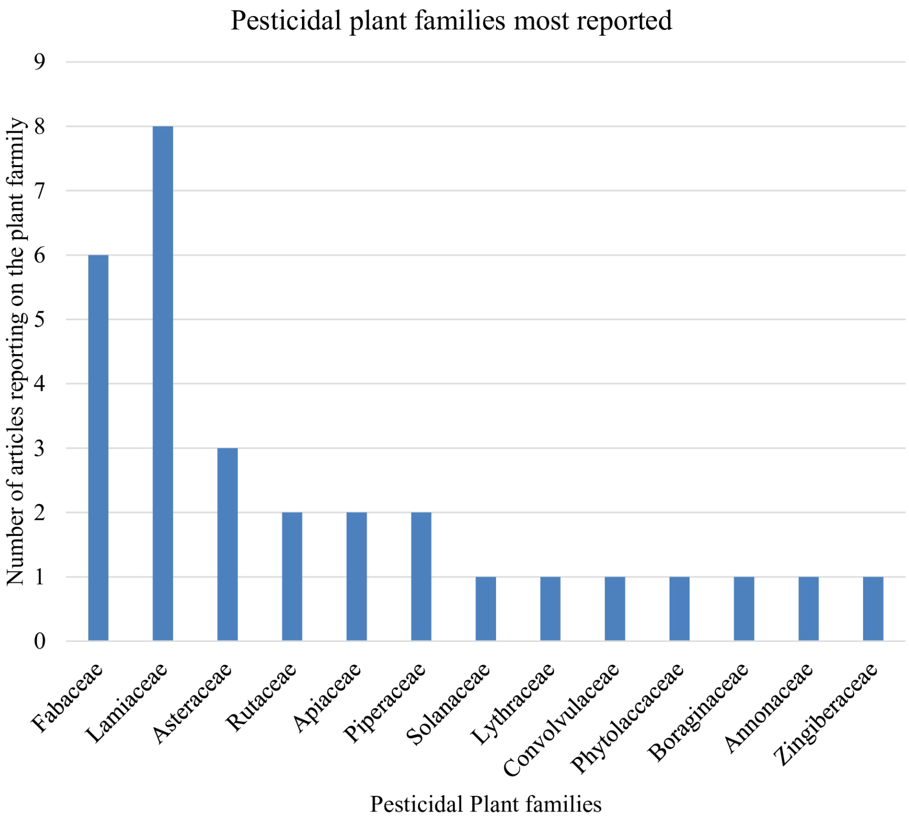

FIGURE 5
Pesticidal plants grouped per plant family.

TABLE 3 Cotton insect pest identified in the reviewed articles.

Feeding Behavior and Destructive stage.	Insect Pest Species	No. articles reported on the insect
Sucking Insects nymphs and adults	*Aphis gossypii + (other species)*	5 (Ghidan et al., 2018; Sakban-Al-Tamimi et al., 2020; Tia et al., 2021; Thakur et al., 2022; Khaleel et al., 2023)
Nymphs and adults	*Bemisia tabaci*	2 (de Oliveira et al., 2018; Tia et al., 2021)
Nymphs and alduts	*Phenacoccus solenopsis*	2 (Modafferi et al., 2004; Alfaro-Corres et al., 2023; Madasamy et al., 2023)
aldults	*Tetranychus urticae*	3 (Campos et al., 2018; Silva et al., 2019)
Chewing Insects, Larvae	*Helicoverpa armigera*	8 (Devi et al., 2014; Patil et al., 2016; Gabriel et al., 2017; Kantrao et al., 2017; Baranitharan et al., 2021; Anees et al., 2022; Asghar et al., 2022) (Campos et al., 2018)
Larvae	*Spodoptera frugiperda*	9 (Giongo et al., 2016; Costa et al., 2017; Lopes et al., 2020; Monteiro et al., 2021; Natal et al., 2021; Bae et al., 2022; Candra Lina et al., 2023; Huang et al., 2024) (Mohammad et al., 2024)
Larvae	*Spodoptera littoralis*	4 (da Costa Inácio et al., 2020; Hazaa et al., 2021; El-Ashmouny et al., 2022; Rafea et al., 2022)
Larvae	*Spodoptera litura*	4 (Bharani and Namasivayam, 2017; Baranitharan et al., 2021; Thakur et al., 2022; Devi et al., 2023)
Larvae	*Spodoptera exigua*	1 (Tia et al., 2021)
Larvae	*Earias insulana*	1 (Kandil et al., 2024)

TABLE 4 Matrices to produce botanical nanoformulations and main results on management of cotton insect pest.

SN	Matrix	Carrier System	Carrier Properties	Botanical Compound	Main Results On Management Of Cotton Insect Pests	Reference
1	Urea-formaldehyde	nanocapsules	The core-shell structures with spherical shapes have the size ranged from 8.30 nm to 17.61 nm, with a median diameter of 12.10 nm and a polydispersity index (PDI) of 0.098.	EOs (Thymol 56.61%, Carvacrol 17.02%), of *T. daenensis.*	The nanocapsulated EOs was more effective as an insecticide against *B. brassicae*, with lower lethal concentrations (LC_{50} and LC_{90}) compared to the raw EOs. Contact toxicity was 208.28 ppm, while fumigant toxicity was 10.55 µl/l air for the nanocapsulated EOs and 18.66 µl/l air for the raw EOs. The product served as an antifeedant, growth regulator, and oviposition deterrent. Target Cotton Insect Pest:	(Heidary et al., 2022)
2	Hydrolate and chitosan	Nano-emulsion	The nano-emulsion showed no creaming or phase separation, Low Viscosity for easier application and handling.	essential oil of *L. multiflora.*	The nano-emulsion significantly controlled the populations of *B. brassicae* and *P. xylostella* compared to synthetic pesticides Karate 5 EC. Other insect tested on were *H. undalis. S. exigua*, *B. tabaci* Higher yields of marketable cabbage heads were recorded in plots treated with the nano-emulsion compared to untreated controls. The nano-emulsion formulation allowed for a controlled release of the essential oil, which prolonged the insecticidal effect and improved persistence in the field, potentially reducing the frequency of applications needed. The nano-emulsion formulation was stable over time, with no degradation observed although the nano-emulsion provided some amount of control over the untreated controls, the differences with the synthetic pesticide were frequently not statistically significant on *H. undalis*, *S. exigua*, and *B. tabaci*	(Tia et al., 2021)
3	$AgNO_3$.	AgNPs	The average size of the synthesized nanoparticles was around 15 nm, with over 80% of the particles ranging between 10 to 20 nm.	extract of *H. indicum* leaves	The AgNPs effectively suppressed several tea garden pests, achieving complete mortality of aphids one day after spraying at a dosage of 20 mg/l, 80% mortality of semi-loopers after two days, and 50% mortality of red slug caterpillars by three days, leading to total mortality by four days.	(Khanra et al., 2018)
4	$AgNO_3$.	biogenic AgNPs	The nanoparticles are reported to be uniform, monodispersive, and highly	pomegranate peel extract (*P. granatum*)	AgNPs effectively inhibited cell viability in SF-21 cell lines, with an IC50 value of 31.2 µg/mL. the nanoparticles induced mortality in various larval	(Bharani and Namasivayam, 2017)

(Continued)

TABLE 4 Continued

SN	Matrix	Carrier System	Carrier Properties	Botanical Compound	Main Results On Management Of Cotton Insect Pests	Reference
			stable, with a size range of 14 to 28 nm		stages of *S. litura*, with higher concentrations leading to 100% mortality in early instars. The nanoparticles negatively affected the growth and physiology of the pest, evidenced by shorter larval and pupal durations, earlier adult emergence, reduced longevity and notable changes in gut physiological parameters, including nutritional indices and gut enzyme activity,	
5	$AgNO_3$	AgNPs	*A. indica*-based AgNPs had an average diameter of 61.70 nm, *P. pinnata*-based AgNPs were 68.80 nm. spherical in shape,	*A. indica and P. pinnata.*	Both *A. indica*-based AgNPs and *P. pinnata*-based AgNPs achieved larval mortality rates of *H. armigera* between 60.00% to 93.33% at concentrations from 500 to 2000 ppm. A. *indica*-based AgNPs zeta potential was −58.96 mV and could be stored for three months without significant loss of bioefficacy, and up to six months with only negligible reduction. Stability of *P. pinnata* AgNPs was less as compared to that of *A. indica*-based AgNPs	(Anees et al., 2022)
6	$AgNO_3$	AgNPs	The nanoparticles were with sizes ranging between 20 to 60 nm, spherical in shape.	leaf extract of *B. officinalis.*	AgNPs demonstrated exceptional larvicidal activity against *S. littoralis*, with an LC_{50} of 0.33 mg/g, making them considerably more toxic than the crude leaf extract, which had an LC_{50} of 22.6 mg/g. AgNPs treatment notably extended the larval stage without significantly affecting pupal duration and achieved 100% mortality at a concentration of 4.0 mg/g, while the crude extract reached only 72% mortality at 100 mg/g, highlighting the nanoparticles' superior efficacy. The LC_{90} value also underscored AgNPs' potency, requiring just 1.7 mg/g for 90% mortality compared to the crude extract's 969.0 mg/g, indicating AgNPs as a powerful and more efficient option for pest management.	(Hazaa et al., 2021)
7	Chitosan, β-cyclodextrin (β-CD) and crosslinked with gum arabic	chitosan nanoparticles	Nanoparticles exhibited a mean diameter of approximately 225.9 nm, spherical, and a polydispersity index (PDI) of 0.185. The zeta potential was measured at +19.3 mV, encapsulation efficiency of 93.9% for carvacrol and 86.9% for linalool.	Carvacrol and linalool	Toxicity assessments showed that the LC_{50} for *H. armigera* was 1.25 mg/mL and the LC_{90} was 2.35 mg/mL, while *T. urticae* had an LC_{50} of 0.98 mg/mL and an LC_{90} of 1.75 mg/mL. The nanoparticles exhibited notable insecticidal activity, providing effective repellency and reducing oviposition. The cytotoxicity assays on cell lines (V79 pulmonary cells and Balb C-3T3 mouse fibroblasts) indicted that encapsulating the botanical compounds decreased toxicity compared to their unencapsulated forms.	(Campos et al., 2018)
8	CuO, ZnO, MgOH, and MgO	nanoparticles	The sizes of the synthesized nanoparticles ranged from 5 nm to 80 nm, spherical in shape	Punicagranatum Peels *O. europaea* Leaves and *C. nobile* Flowers	The study's main findings emphasized the efficacy of synthesized nanoparticles against the *M. persicae*. The LC_{50} values were as follows: CuONPs at 0.15 ppm, ZnONPs at 0.42 ppm, MgOHNPs at 0.15 ppm, and MgONPs at 1.24 ppm. For LC90, CuONPs were at 0.15 ppm, ZnONPs at 0.53 ppm, MgOHNPs at 0.15 ppm, and MgONPs at 1.15 ppm. The results indicated that biosynthesized magnesium hydroxide nanoparticles (MgOHNPs) exhibited the highest aphicidal activity, closely followed by copper oxide nanoparticles (CuONPs). The effectiveness was assessed through mortality percentages recorded at 24, 48, and 72 hours	(Campos et al., 2018)
9	soybean liposomes and chitosan	nanoencapsule	The nanocapsules has a sizes less than 200 nm	Extract of *R. graveolens*	The *R. graveolens* dichloromethane extract (B1) showed the highest insecticidal activity, reducing Sf9 cell viability by over 50%, exceeded commercial insecticide chlorpyrifos, which reduced viability by around 50%. Morphological analysis of cells treated with B1 extract revealed chromatin condensation and fragmentation, suggesting an organized cell death process. B1 extract from *R. graveolens* was the most potent,	(Ghidan et al., 2018)

(Continued)

TABLE 4 Continued

SN	Matrix	Carrier System	Carrier Properties	Botanical Compound	Main Results On Management Of Cotton Insect Pests	Reference
					reducing viability by over 50% at the tested concentration of 100 µg/mL. The study showed that chitosan nanoemulsions provided a fast and total release of extracts, while liposome-based systems facilitated a more delayed release.	
10	chitosan cross-linked with tripolyphosphate (TPP) Glutaraldehyde	nanoparticles	The size of the nanoparticles varied between 32-90 nm for CSNs. The diameters were approximately 122.7 nm for CSNs-TPP-PONNEEM and 243.5 nm for CSNs-GLA-PONNEEM. spherical shape	PONNEEM®, which contains: Neem oil Karanj oil Azadirachtin Karanjin	CSNs-TPP-PONNEEM achieved 90.2% mortality against *H. armigera* at 0.3% concentration, compared to 73.6% for PONNEEM alone. CSNs-TPP-PONNEEM demonstrated 88.5% antifeedant activity, while PONNEEM alone reached 100% at 0.3% concentration The treatments caused developmental abnormalities in larvae, indicating significant growth regulation.	(Gabriel et al., 2017)
11	$AgNO_3$	AgNPs	The synthesized AgNPs typically range in size from 10 to 100 nm, spherical shape,	Leaf extracts of *F. religiosa* and *F. benghalensis*	The biosynthesized AgNPs combined with permethrin showed lethal concentrations of LC_{50} at 30 µg/g and LC_{90} at 80 µg/g in the diet, achieving high mortality rates for *H. armigera*. AgNPs enhanced solubility within the artificial diet, improving absorption and bioavailability of active ingredients in the insect's gut. The nanoparticles allowed for controlled release, providing prolonged insecticidal activity and reducing application frequency.	(Kantrao et al., 2017)
12	Gelatin	Gelatin-based nanoparticles (GBNPs)	EOs nanoparticles of *P. hispidinervum* 100 nm (± 2 nm), while those of *P. aduncum* ranged between 175 nm (± 4 nm) and 220 nm (± 4 nm). The zeta potentials were –43.5 mV (± 3 mV) for *P. hispidinervum* and –37.5 mV (± 2 mV) for *P. aduncum*. Both types of nanoparticles were nearly spherical, well-dispersed, and displayed a uniform structure.	EOs from *P. aduncum* and *P. hispidinervum*.	*P. aduncum* EOs exhibited high insecticidal activity, with LC_{50} and LC_{90} values of 48.1 µg/mL and 72.0 µg/mL, respectively, against Aedes aegypti larvae after 24 hours. It showed an LC_{50} of 56.5 µg/mL for T.urticae and 219.4 µg/mL for *C. lataniae* (palm aphids). Similarly, *P. hispidinervum* EOs had a 24-hour LC_{50} of 81.3 µg/mL and LC_{90} of 138.9 µg/mL for mosquito larvae, with LC_{50} values of 84.3 µg/mL for spider mites and 148.1 µg/mL for palm aphids. Encapsulating these EOs in gelatin nanoparticles enhanced solubility, bioavailability, and extended release, maintaining lethal concentrations for up to 140 hours, reducing application frequency.	(Silva et al., 2019)
13	Poly (ε-caprolactone) (PCL), Poly (β-hidroxibutirate) (PHB) and Poly (methyl methacrylate) (PMMA)	Nanocapsules and nanospheres		*A. indica*	The estimated LC_{50} of commercial neem oil for *S. frugiperda* first instar larvae was 0.64%, or 3.87 mg azadirachtin/L. The nanocapsule formulation with poly (methyl methacrylate) at 0.25 grams achieved 48.75% mortality. The nanospherical formulation with poly (methyl methacrylate) at 0.25 grams resulted in 45.00% mortality. The nanocapsule formulation with poly(ε-caprolactone) at 0.75 grams also showed 45.00% mortality. The nanocapsule formulation with poly(β-hidroxibutirate) at 0.25 grams reached 42.50% mortality. The commercial neem oil (Organic Neem) demonstrated a 100% mortality rate. None of the nanoformulations surpassed the residual efficacy of the commercial neem oil, which consistently showed 100% mortality.	(Giongo et al., 2016)
14	latex serum and silver oxides.	latex- LAgNPs		Cardiac glycosides, terpenes, and phenolic compounds	Injections of 5 µl or 10 µl of LAgNPs significantly increased the mortality rate *S. littoralis* larvie compared to controls, with mortality rates improving with higher nanoparticle concentrations. The latex serum exhibited strong antifeedant properties, with activity ranging from 68.1% to 99.3%	(Mohamed et al., 2023)

(Continued)

TABLE 4 Continued

SN	Matrix	Carrier System	Carrier Properties	Botanical Compound	Main Results On Management Of Cotton Insect Pests	Reference
				from *C. procera*: :	depending on the concentration. Higher concentrations of latex serum resulted in greater deterrence, highlighting its effectiveness in preventing larvae from feeding. The latex-synthesized nanoparticles (LAgNPs) showed significantly enhanced antifeedant activity compared to the latex serum alone. At 2% and 5% concentrations, LAgNPs demonstrated substantial antifeedant effects, with the 5% concentration showing about four times the activity of the 2% concentration. The starvation percentage for larvae treated with 5% LAgNPs was 17.75%, indicating a strong deterrent effect.	
15	zein	zein nanoparticles	The nanoparticles had a mean diameter of 234 to 302 nm, with zeta potentials between -15 mV and -20 mV. They exhibited a smooth, spherical shape, and had a polydispersity index (PDI) of 0.34 to 0.52,	Geraniol, Eugenol and Cinnamaldehyde	Nanoencapsulation improved the solubility of botanical compounds compared to non-encapsulated forms. The study demonstrated controlled release of active compounds influenced by temperature, with a diffusion-based mechanism being the primary release method. Cinnamaldehyde showed the highest release rates, particularly at elevated temperatures.	(Monteiro et al., 2021)
16	Chitosan and gum arabic	Chitosan/gum arabic nanoparticles		geraniol,	The nanoformulated product demonstrated greater efficacy against whitefly, achieving lower LC_{50} and LC_{90} values than the control, though exact values weren't specified. Encapsulation enhanced geraniol's solubility, bioavailability, and stability, preserving its properties for 120 days without significant degradation. With a zeta potential range of -21 to +35 mV, the nanoparticles showed good stability due to electrostatic repulsion. Controlled release was successfully achieved through a temperature-sensitive diffusion mechanism, which prolonged the insecticidal action of geraniol, effectively meeting the study's goals.	(de Oliveira et al., 2018; De Oliveira et al., 2018)
17	AgNO3 and leaf extract of Euphorbia hirta	AgNPs	The synthesized AgNPs, sized 30–60 nm with spherical and cubic shapes as shown by SEM, are generally considered stable in suspension if their zeta potential exceeds ±30 mV.	leaf extract of *E. hirta*,	The LC_{50} values for Helicoverpa armigera instars and pupae ranged from 2.905 ppm to 70.805 ppm, with LC_{90} values from 9.402 ppm to 145.734 ppm, and the first instar had an LC_{50} of 33.383 ppm and LC_{90} of 97.146 ppm. The synthesized AgNPs, sized 30-60 nm, showed enhanced solubility and bioavailability, improving their interaction with the pest and contributing to higher efficacy than the control, with 94% larval mortality at 100 ppm. The mode of action includes disrupting gut physiology in larvae and potentially damaging cellular structures due to the high reactivity of the nanoparticles, which interfere with biological processes. The AgNPs, synthesized from Euphorbia hirta, demonstrated improved larvicidal activity, better targeting of the larval stages of Helicoverpa armigera, enhanced stability, and suggested controlled release, though further research is needed.	(Devi et al., 2014)
18	ZnO and leaf extract of *M. communis* L	ZnONPs	The synthesized ZnONPs, with a size range of 40 to 60 nm, were semi-spherical in shape, with slight deviations,	leaf extract of *M. communis* L	The synthesized ZnONPs exhibited significant insecticidal efficacy, with 77.37% mortality in nymphs and 53.65% in adults of *M. persicae* at 100 ppm after 3 days. Control treatments resulted in 33.31% mortality for nymphs and 23.54% for adults, showing that ZnONPs were approximately 2.5 times more effective. The ZnONPs demonstrated good solubility, enhancing their bioavailability and facilitating better absorption and interaction with pests.	(Khaleel et al., 2023)

(Continued)

TABLE 4 Continued

SN	Matrix	Carrier System	Carrier Properties	Botanical Compound	Main Results On Management Of Cotton Insect Pests	Reference
19	EOs of *A. sativum* strategizing on energy input	nano-emulsions (Sonicated, Sonicated and microfluidized, Microfluidized)	The nano-emulsions produced by high-energy methods (SN, SH, HPM) had droplet sizes below 200 nm, while the RAW emulsion exhibited larger droplets around 500 nm. All formulations displayed negative zeta potential values. spherical shape	essential oil of A. sativum	The study evaluated nano-emulsions of garlic EOs against *P. citri*, achieving 100% mortality at a 2.5% concentration. The nano-formulations significantly outperformed the RAW emulsion, which showed lower efficacy. The formulations were produced using high-energy methods (SN, SH, HPM), resulting in enhanced solubility and bioavailability, which improved insecticidal activity. The nano-emulsions had stable droplet sizes under 200 nm and showed superior efficacy compared to the RAW emulsion, which had lower insecticidal activity. The mode of action involved contact toxicity and potential fumigation effects from sulfur compounds in the garlic EOs	(Modafferi et al., 2004)

(nanocapsulated), LC_{90} 2367.62 ppm (raw EOs) (Heidary et al., 2022) indicating increased efficacy with the nanocapsulated form. Carvacrol and linalool co-loaded in chitosan nanoparticles showed LC_{50} values of 1.25 mg/mL on *H. armigera* and 1.5 mg/mL on *T. urticae*, LC_{90} 2.5 mg/mL for *H. armigera* and 3.0 mg/mL for *T. urticae* (Campos et al., 2018) demonstrating increased efficacy. Encapsulated EOs against *A. aegypti*, *T. urticae*, and *C. lataniae* reported LC_{50} values of 48.1 µg/mL, 56.5 µg/mL, and 148.1 µg/mL respectively (Silva et al., 2019). Neem-based nanoformulations against *S. frugiperda* had an LC_{50} of 0.64% (3.87 mg azadirachtin/L) (Giongo et al., 2016). The LC_{50} values of *B. ocimum* EOs nanoemulsions was 45 mg/L, and *O. marjorana* EOs nanoemulsions was 188 mg/L against *A. craccivora* while LC_{50} values of *B. ocimum* EOs was 992 mg/L and *O. marjorana* EOs was 3162 mg/L on same insect (Abdelaal et al., 2021).

4 Discussion

4.1 Potential of botanical nanoformulations in cotton insect pest management

In the reviewed articles botanical nanoformulations shown significant promise for sustainable cotton pest management by enhancing the efficacy of botanical extracts and EOs (de Oliveira et al., 2018; Ibrahim, 2019). Nanoemulsions systems reportedly to address limitations of EOs applications by preventing degradation, improving residue half-life, and enhancing solubility, delivery, and mobility (Campos et al., 2018; Abdelaal et al., 2021; Rafea et al., 2022). In research conducted by Abdelaal et al. (2021) demonstrated that nanoemulsified *B. ocimum* and *O. marjorana* EOs had significantly lower LC_{50} values against *A. craccivora* (45 mg/L and 188 mg/L, respectively) compared to their non-nanoemulsified counterparts (992 mg/L and 3162 mg/L, respectively). Similarly, nanoemulsions of *L. multiflora* EOs significantly reduced *B. brassicae* populations (28.48 ± 0.2%) (Manjesh et al., 2022) highlighting their potential to overcome limitations of traditional EOs applications cotton pest management.

Polymeric nanomaterials also exhibit enhanced pest management efficacy. Urea-formaldehyde nanocapsules demonstrate a lower LC_{50} of 208.28 ppm and LC_{90} 1026.44 as compared to 702.57 ppm 2367.62 ppm of raw EOs against *B. brassicae* (Heidary et al., 2022). Chitosan nanoparticles co-loaded with carvacrol, and linalool have LC_{50} values of 1.25 mg/mL against *H. armigera* and 1.5 mg/mL against *T. urticae* (Campos et al., 2018). Gelatin nanoparticles yield LC_{50} values of 48.1 µg/mL for *A. aegypti*, 56.5 µg/mL for *T. urticae*, and 148.1 µg/mL for *C. lataniae* (Silva et al., 2019). The polymeric nanoparticles demonstrated significantly higher insecticidal activity compared to non-nanoparticle products. In research conducted by Gabriel et al. (2017) Chitosan nanoparticles (CSNs)- tripolyphosphate (TPP)-PONNEEM achieved a 90.2% mortality rate third instar of *H. armigera* at a 0.3% concentration surpassing neem oil's 73.6% mortality at the same concentration (Gabriel et al., 2017). This improvement in effectiveness highlights the benefits of nano-encapsulation, which not only enhanced the insecticidal properties of the active ingredient, but also induces developmental abnormalities in pests, leading to malformed adults and smaller pupae (Gabriel et al., 2017). In research conducted by Bae et al. (2022) nanoencapsulated neem formulations using whey protein showed a significant reduction in LC_{50} values over time, dropping from 24.1 mg/mL on day one to 3.0 mg/mL by day 11, compared to bulk neem seed extract, which only decreased from 35.3 mg/mL to 8.5 mg/mL over the same period (Bae et al., 2022). Encapsulating azadirachtin in lignin microparticles accelerated mortality 100% faster in *S. frugiperda* and *D. saccharalis*, than non-encapsulated neem extracts (Costa et al., 2017) further highlighting the benefits of nanoencapsulation for cotton insect pest control. These results indicate that polymeric nanoformulations offer superior pest control efficacy at lower concentrations, making them a promising avenue for developing effective botanical nanopesticides.

Botanical nanoformulations utilizing metallic nanoparticles (AgNPs, MgONPs, CuONPs AuNPs and ZnONPs) enhanced the stability, efficacy, controlled release and targeted deliver. Biosynthesis AgNPs using Oxymatrine resulted in an LC_{50} of 0.5 ml/L and an LC_{90} of 1.5 ml/L against *A. gossypii*, significantly enhanced mortality compared to controls (Sakban-Al-Tamimi et al., 2020). Biogenic

AgNPs showed an LC_{50} of 31.2 μg/mL against third instar of *S. litura*, outperforming conventional insecticides (Bharani and Namasivayam, 2017) while AgNPs from *B. officinalis* had LC_{50} and LC_{90} values of 0.33 mg/g and 1.7 mg/g against third instar of *S. littoralis* (Hazaa et al., 2021). *Rosmarinus officinalis* AgNPs showed LC_{50} values of 16.75% and 18.65% against *E. insulana* and *P. gossypiella*, respectively (Kandil et al., 2024). Siliver nanoformulations of *A. indica* and *P. pinnat*a against second instar *H. armigera* exhibited LC_{50} values of 500 ppm and 600 ppm with LC_{90} values of 2000 ppm and 1500 ppm respectively (Anees et al., 2022). Research conducted by Asghar et al. (2022) stage-specific efficacy for neem AgNPs was observed where toxicity increased as larvae progressed to later instars, with LC_{90} values rising from 202.71 ppm in the third instar to 240.90 ppm in the fifth instar of *H. armigera* (Asghar et al., 2022). Zinc oxide nanoparticles (ZnO NPs) synthesized from neem extracts were also reported to enhance effective control of *H. armigera* where they exhibited LC50 values of 127.79 ppm, 114.069 ppm, and 155.38 ppm for the third, fourth, and fifth instars, respectively (Asghar et al., 2022). Green-synthesized nanoparticles from *E. hirta* showed an LC_{50} of 2.905 ppm against *H. armigera (*Devi et al., 2014). Silver nanoparticles from *A. catechu* reported LC_{50} values of 71.04 mg/mL for *S. litura* and 85.33 mg/mL for *H. armigera* (Baranitharan et al., 2021). Screening of zinc oxide and copper oxide nanoparticles against *S. frugiperda* yielded LC50 values of 520 ppm for ZnONPs and 440 ppm for CuONPs (Mohammad et al., 2024). Utilizing metallic nanoparticles demonstrates a broad spectrum of insecticidal activity and highlights the potential of botanical nanoformulation in creating targeted and efficient cotton insect pest management solutions although the long-term effects of metallic nanomaterials remain to be uncovered.

Botanical nanoformulations, encompassing nanoemulsions, polymeric nanoparticles, and metallic nanoparticles, represent a transformative approach in cotton insect pest management. Despite the promising results of botanical nanoformulations, some studies have pointed to limitations in efficacy compared to commercial botanical products. Out of 39 articles reviewed, one research article by Giongo et al. (2016) demonstrated that neem oil, when formulated as nanoemulsions, showed a significantly lower efficacy than commercial neem oil. The commercial neem oil achieved 100% mortality of third instar of *S. frugiperda* with an LC_{50} of 0.64% (3.87 mg azadirachtin/L), while the nanoformulations only reached a maximum mortality rate of 48.75% at a higher concentration (Giongo et al., 2016). This highlights that, while nanoformulations offer distinct advantages in terms of prolonged pest control and reduced environmental impact, they may not always provide immediate lethal effects on par with synthetic chemical insecticides.

Although the performance of botanical nanoformulations is evidently, the reviewed articles primarily focused on chewing insects (particularly Lepidoptera, such as *H. armigera*, *S. frugiperda*, *S. littoralis* and a few sucking insects (*B. tabaci*, *P. solenopsis* and Aphis species). The emerging serious cotton insect pests in developing countries in particular Tanzania include *A. biguttula*, *T. cinnabarinus*, *E. insulana* and *T. tabaci*, were less studied hence a gap in the current research landscape (Table 3) (Gabriel et al., 2017; De Oliveira et al., 2018; Ibrahim et al., 2022).

4.2 Botanical nanoformulations synthesis methods and modes of action

Botanical nanoformulations for cotton insect pest management in the reviewed articles utilized several synthesis methods, each with unique advantages (Bharani and Namasivayam, 2017; Gabriel et al., 2017; Tia et al., 2021; Asghar et al., 2022; Ibrahim et al., 2022; Khaleel et al., 2023)). The reviewed articles showed polymeric nanoparticle synthesis utilized biodegradable polymers like chitosan and PLGA for controlled release and stability (Gabriel et al., 2017; De Oliveira et al., 2018; Ibrahim et al., 2022) Biogenic synthesis used plant extracts and microorganisms to eco-friendly stabilize nanoparticles, producing AgNPs and biogenic ZnONPs (Bharani and Namasivayam, 2017). Green Synthesis applied plant-based agents for high biocompatibility, including neem-based formulations (Patil et al., 2016; Al Jabri et al., 2022)). Chemical precipitation involved reactions between metal salts and reducing agents for reproducible nanoparticles like ZnONPs (Asghar et al., 2022). Lastly, nanoemulsification stabilized EOs in nanoscale emulsions, enhanced solubility and bioavailability (Tia et al., 2021; Rafea et al., 2022).

The mode of action and synergism of these nanoformulations are influenced by nanomaterial used, synthesis method and the nature of the bioactive compounds encapsulated. In the reviewed article AgNPs were widely studied and about 29% of the studies applied silver oxide as the nanomaterial. Silver nanoparticles exhibited neurotoxic effects, leading to paralysis and death in pests such as *A. gossypii* and *H. armigera* (Sakban-Al-Tamimi et al., 2020; Heidary et al., 2022). Silver nanoparticles shown significant larvicidal activity, which include disruption of physiological processes and inhibition of gut protease activity (Bharani and Namasivayam, 2017; Hazaa et al., 2021). The *R. officinalis* AgNPs treated pests exhibited extended developmental periods *E. insulana* and *P. gossypiella* up to 34.9 and 33.83 days as compared to 24.3 and 21.9 days of untreated insect pests respectively (Kandil et al., 2024) and reduced survival rates, emphasizing the nanoparticles' ability to disrupt pest growth and development. The synthesis of AgNPs from *B. officinalis* leaves enhanced larval mortality compared to crude extracts, showcasing their synergism and potent insecticidal properties (Bharani and Namasivayam, 2017; Huded et al., 2023).

Chitosan nanoparticles exhibited antifeedant and larvicidal activities against various pests (Gabriel et al., 2017; Campos et al., 2018; De Oliveira et al., 2018; Ibrahim et al., 2022). The reviewed studies demonstrated that chitosan nanoparticles enhanced stability and bioavailability of EOs, such as those from *T. daenensis*, leading to improved pest management (Heidary et al., 2022). Their ability to inhibit acetylcholinesterase further signifies their potential in disrupting neurophysiological functions in insects, providing a synergistic effect when used in conjunction with other biopesticides (Asghar et al., 2022; Devi et al., 2023). Gelatin nanoparticles and urea-formaldehyde nanocapsules are biopolymer that encapsulated EOs, botanical extracts and their stability and effectiveness were improved (Silva et al., 2019). In research conducted by Silva et al. (2019) demonstrated that gelatin-based nanoparticles effectively encapsulate EOs from *P. aduncum* and *P. hispidinervum*, achieving encapsulation efficiencies of 79.2% at 500 µg/mL and 84.5% at 1,000 µg/m. These nanoparticles maintain lethal concentrations for over 140 hours, enhancing insecticidal efficacy through controlled release and improved solubility (Giongo et al., 2016).

Zinc oxide nanoparticles and CuONPs act through cuticle penetration and metabolic disruption, effectively controlling pests like *S. frugiperda* (Al Jabri et al., 2022; Devi et al., 2023; Mohammad et al., 2024). Zinc oxide nanoparticles and CuONPs when used alongside neem-based formulations, their efficacy was significantly enhanced, demonstrating a synergistic approach to pest management (Mohammad et al., 2024). Gold nanoparticles was reported to enhance effective delivery systems, enhanced bioavailability of bioactive compounds, improved insecticidal activity while reduced environmental impact (Patil et al., 2016; Al Jabri et al., 2022; Asghar et al., 2022; Devi et al., 2023). Their modes of action involved disruption of digestive enzymes and metabolic processes (Patil et al., 2016).

The diverse nanomaterials (silver, chitosan, zinc oxide, copper oxide, and gold nanoparticles) employed in botanical nanoformulations for cotton insect pest management exhibited varied modes of action, including neurotoxicity, antifeedancy, cuticle penetration, metabolic disruption, and enhanced bioavailability of bioactive compounds, often exhibiting synergistic effects when combined with botanical insecticides altogether are reported to be safe for non-targeted organism like was highlited by Modafferi et al. (2004) that nanoemulsions of *A. sativum* EOs showed significant insecticidal activity against *P. citri* without harming non-target species, the *Apis mellifera* L.

(Baker et al., 2016; Siddiqua et al., 2016; Huded et al., 2023) The reviewed literature demonstrated that nanoformulations significantly enhanced the efficacy, and delivery of biopesticides by improving their solubility, stability, and controlled release properties (Giongo et al., 2016; Costa et al., 2017; Gabriel et al., 2017; Ghidan et al., 2018; Khanra et al., 2018; Silva et al., 2019; Lopes et al., 2020; Baranitharan et al., 2021; Tia et al., 2021; Asghar et al., 2022; Anees et al., 2022; Bae et al., 2022; Metwally et al., 2022; Rafea et al., 2022; Madasamy et al., 2023; Kandil et al., 2024; Mohammad et al., 2024).

4.3 The effect of botanical nanoformulations on non-target, persistence, and biodegradability

The reviewed articles demonstrated that botanical nanoformulations enhanced the stability, bioavailability, and controlled release of plant extracts, thereby improving their cytotoxic effects and retention of bioactive compounds. In the research conducted by Alfaro-Corres et al. (2023) demonstrated that nanoparticles synthesized from *C. chinense* leaf extracts exhibit significant stability, with Zeta potential values approaching 200 mV for bimetallic nanoparticles (Cu/Mn and Zn/Cu), suggesting prolonged insecticidal properties compared to unformulated extracts (Alfaro-Corres et al., 2023). Silver encapsulated extracts of *H. indicum* characterized by a particle size of approximately 200 nm and low polydispersity, have demonstrated effective interaction with insect cell membranes, resulting in chromatin condensation while displaying reduced toxicity to human cells (PA1 cell line) (Khanra et al., 2018).

The encapsulation of camptothecin (CPT) was found to enhance its stability and targeted efficacy, particularly in the alkaline environments typical of lepidopteran midguts (Huang et al., 2024). In research conducted by Huang et al (Huang et al., 2024)demonstrated that using a star polycation (SPc) nanocarrier significantly boosts the efficacy and persistence of CPT. Additionally, research by Yan et al. (2021) revealed that the osthole/SPc complex does not negatively affect non-target predators, such as ladybird beetles, indicating that botanical nanoformulations can be designed to minimize harm to beneficial species in the ecosystem. Similarly, research conducted by Monteiro et al. (2021) showed that formulations containing limonene and carvacrol did not exhibit phytotoxic effects on *Phaseolus vulgaris* plants, suggesting a lower risk to beneficial plants in agricultural settings.

Chitosan nanoemulsions facilitated rapid release of active ingredients, whereas liposomal formulations provided delayed release, leading to greater effectiveness than non-encapsulated extracts (Lopes et al., 2020). These formulations maintain stability without phase separation and benefit from enhanced solubility. Controlled release mechanisms have been shown to prolong insecticidal effects and improve overall efficacy (Tia et al., 2021). Additionally, in research conducted by Kandil et al. (2024) reported that AgNPs maintain stability, effective targeting, and good solubility, thereby enhancing pest control and extending bioavailability against *H. armigera* (Gabriel et al., 2017).

5 Challenges, opportunities and future directions botanical nanoformulations in developing countries

Despite the potential of botanical nanoformulations, several challenges and limitations have been identified for their practical application.

5.1 Variability in nanoparticle size and stability

A significant challenge across the studies is the variability in the size and stability of nanoparticles due to environmental factors, like temperature and light, which affect their effectiveness as insecticides (Sola et al., 2014; Chakraborty and Mondal, 2016; Attia, 2018; Reddy and Chowdary, 2021). For instance, the biosynthesis of nanoparticles may lead to inconsistencies in their characterization, impacting reliability in agricultural applications (Tia et al., 2021; Anees et al., 2022) (Tia et al., 2021). However, improving synthesis techniques using controlled biogenic and polymeric methods can standardize nanoparticle properties, ensuring consistent application and efficacy.

5.2 Limited field trials

Most studies were confined to laboratory settings, with only 6% extending to semi-field and/or field trials. This presents an opportunity for scaling up field trials across diverse agroecological zones to validate real-world applicability and address variability in pest behavior under different conditions.

5.3 Toxicity

The long-term ecological impacts of nanoformulations in agriculture was not yet well identified from the articles reviewed. The potential toxicity associated with biogenic nanoparticles may adversely affect non-target organisms and beneficial insects. This raises ecological implications regarding the accumulation of nanoparticles in the environment, which can threaten biodiversity (Heidary et al., 2022). Additionally, ensuring uniform distribution and penetration of nanoparticles in plant tissues was shown as a challenge, as inconsistent applications can lead to variable pest control outcomes (Khanra et al., 2018). However, the fact that plants were known to have less toxicity encouraged an advancement in nanotechnology that enables the development of targeted formulations tailored to specific pests. Additionally biogenic nanoparticles, derived from natural sources, exhibit low toxicity to non-target species, making them an environmentally sustainable choice.

5.4 Regulatory barriers

Regulatory hurdles and a lack of infrastructure for nano-formulation production and distribution pose significant barriers to their commercialization (Gupta et al., 2021). Addressing these challenges requires collaborative efforts between researchers, policymakers, and industry stakeholders to promote the development and deployment of sustainable insect pest management solutions (Ibrahim, 2019; El-Naby et al., 2020; Priyanka et al., 2020; Vichakshana et al., 2022). The increasing demand for eco-friendly pest control solutions presents a market opportunity for these formulations, which can enhance agricultural productivity while reducing health risks and environmental impacts.

6 Recommendation

To ensure the successful adoption of botanical nanoformulations, several key steps must be taken. Large-scale, multi-location field trials are essential to evaluate their performance under real-world conditions, providing robust data on efficacy and scalability. Farmer training programs should be developed to educate smallholder farmers on the benefits, application techniques, and safety protocols for these formulations. Collaboration with policymakers is crucial to establish regulatory frameworks that ensure the safe production, distribution, and use of botanical nanoformulated products while fostering trust among stakeholders. Efforts should also focus on cost optimization through research and innovation, making botanical nanoformulations affordable and accessible to resource-constrained farmers. Finally, these solutions must be seamlessly integrated into existing Integrated Pest Management (IPM) frameworks to enhance pest control strategies and promote sustainable cotton insect pest management practices.

7 Conclusion

Botanical nanoformulations represent a transformative step toward sustainable cotton pest management in developing countries. Their integration into farming practices can reduce dependency on synthetic pesticides in management of cotton insect pests in developing countries, promote biodiversity, and align with global efforts toward environmentally responsible agriculture. These eco-friendly alternatives to synthetic pesticides enhance efficacy, stability, targeted delivery and environmental compatibility, addressing critical challenges in cotton production sustainability. By advancing formulation techniques, expanding field trials, and fostering collaborations among stakeholders, these innovations can significantly reduce dependency on synthetic pesticides, transforming the cotton production systems in developing countries. Future research must focus on overcoming scalability barriers and integrating these formulations into comprehensive pest management frameworks to achieve long-term agricultural sustainability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

RL: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. AM: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript.

Summarizing large articles and sentences phrasing.

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