Research Paper

Formulation of Botanical Extracts as Nanoemulsion: Towards Sustainable Pest Management in Agriculture – A Review

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ARTICLE INFO

Article history:
Received: 10 January 2023
Revised version received: 16 February 2023
Accepted: 15 March 2023

Citation:
Hadji, T.K.A.I., Senanayake, N.S., Dharmasena, A., (2023). Formulation of Botanical Extracts as Nanoemulsion: Towards Sustainable Pest Management in Agriculture – A Review. *Tropical Agriculturist, 171* (1), 1-22.

Abstract

Botanical extracts have long been recognised for their pest and disease control potential. However, challenges such as poor stability and limited efficacy often hinder their practical application in agriculture. In recent years, the emergence of nanoemulsion formulations has offered a promising solution to overcome these limitations. Nanoemulsions are isotropic systems of two immiscible liquids (oil and water) combined to generate a single formulation. The nano size and surface characteristics of the droplets play a crucial role in enhancing the biological behaviour of the formulation. This review article aims to assess the potential of employing nanoemulsion formulations containing botanical extracts as a viable and environmentally sustainable strategy for insect pest management in Sri Lankan agriculture. The article discusses the potential botanicals available in Sri Lanka that can be developed as nanoemulsions, examples of plant extracts improved as nanoemulsions in other countries, advantages of nanoemulsion formulations, formulation techniques, optimisation strategies, and their potential applications in pest management. It emphasises the need for further research and practical implementation to fully harness the potential of nanoemulsion formulations for sustainable agricultural pest management in Sri Lanka.

Keywords: **Botanical extracts, Environmental sustainability, Nanoemulsion formulations, Pest management**

Introduction

Managing pests and diseases in agricultural crops is a significant challenge worldwide, including in Sri Lanka. Conventional pest control in crop cultivation often relies on synthetic pesticides. Synthetic chemical insecticides are the primary and the most common option for controlling insect pests (Horowitz *et al.,* 2020; Thakur *et al.,* 2018). However, the indiscriminate application of these insecticides is a major concern as they affect environmental and human health. However, the ability of insect pests to evolve insecticide resistance has made insect pest management extremely difficult. (Suhag *et al.*, 2021). Repeated exposure of insects to insecticides with the same mode of action has significantly enhanced the development of insecticide resistance. Resistance development is generally managed using insecticides with different modes of action in conjunction with other control measures (Marasinghe *et al.,* 2022). Under these circumstances, there is a growing need for sustainable and environmentally friendly insect control alternatives that are effective with minimal negative impacts.

Botanical extracts derived from plants have long been recognised for their potential as eco-friendly alternatives to synthetic pesticides in agricultural pest management. Sri Lanka, rich in biodiversity and traditional knowledge of plant-based remedies, offers a diverse range of botanical resources for agricultural pest management. Regardless of the pesticidal properties, the practical application of botanical extracts in the field encounters challenges, including their low water solubility. The instability of active molecules in botanical extracts can result in rapid degradation under various environmental conditions, diminishing their effectiveness as pest control agents (Pavoni *et al.,* 2020). The variable composition of botanical extracts further contributes to inconsistent efficacy against insect pests. Overcoming these challenges is crucial to fully harnessing the potential of botanical extracts and promoting their sustainable use in agriculture.

Nanotechnology - based techniques have become available to overcome the limitations of botanical extracts to use in insect pest management. Nanoemulsions improve the bioavailability of plant extracts. Nanosize and surface properties of droplets enhance the formulation's biological activity and feasibility of botanical insecticides, effectively addressing the challenges associated with their use (Sharma *et al.,* 2020). By harnessing the power of nanotechnology, researchers and agricultural practitioners can overcome the limitations of traditional botanical extracts and develop practical, effective, eco-friendly, and economically viable solutions for insect pest management.

The primary objective of this review article is to examine the potential botanicals available in Sri Lanka that can be developed as nanoemulsions, examples of plant extracts improved as nanoemulsions in other countries and elucidate the potential benefits of employing nanoemulsion formulations incorporating botanical extracts as a strategic approach for effective pest management within the context of Sri Lankan agriculture.

Botanical extracts

Various plant extracts, including essential oils and solvent extracts obtained from different plant families, process insecticidal properties (Oviedo *et al.,* 2020). Due to their biodegradability, low toxicity, and environmentally friendly nature, botanical extracts are considered relatively safe for human and environmental health (Omar *et al.,* 2016; Thiviya *et al.,* 2022). The growing demand for organic agricultural products has increased interest in plant-based insecticidal products (Singh, 2014; Omar *et al.,* 2016). However, the widespread use of botanical extracts has been hindered by several factors (Campos *et al.,* 2019), including a short shelf life, poor physicochemical stability, low water solubility, high volatility, inconsistent effectiveness, and technological challenges (Campos *et al.,* 2019; Pavoni *et al.,* 2020).

Use of botanical extracts in insect pest management in Sri Lanka

The utilisation of botanicals in insect pest management has garnered significant attention in Sri Lanka due to their environmentally friendly, cheap, and locally produced characteristics. Studies published over the past 26 years in Sri Lanka on liquid botanical crude extracts tested against insect pests of crops are summarised in Table 1. Only a few researchers have tested and reported the bioactive compounds of evaluated botanical extracts.

However, despite the increasing number of recent studies on using plant extracts as botanical insecticides, available commercial formulations are scarce as bioinsecticides in the country. Azadirachtin A 7.5 g L^{-1} EC (LakGro Neem) is the only locally produced plant-based insecticide formulation registered in Sri Lanka.

Botanical pesticide formulation

Developing suitable formulations through botanical extracts is necessary to enhance their effectiveness, safe pesticide handling, and safe application and maximise pesticide efficacy before their effective utilisation in agricultural fields. While synthetic pesticides have adverse environmental impacts, they often exhibit high specificity towards targeted pests. Therefore, as Shah & Wani (2016) suggested, rigorous standardisation of botanical insecticides is essential to ensure their effectiveness compared to synthetic counterparts. To accomplish this, the pesticide formulation should be chemically stable and physically homogeneous under all possible storage circumstances, allowing for accurate application of the minimal effective dose to the target area and making them more acceptable for usage in the field (Hazra, 2019).

Table 1. List of liquid botanical crude extracts tested against insect pests of crops in

No.	Plant source	Extract type	Bioactive compounds
1.	*Allium sativum* cloves (E; Garic, S: Sudu loonu)	Kerosene and water	n.d.*
2.	*Annona spp.* seeds of mature fruits (S: Anoda)	Aqueous extract	n.d.
3.	*Annona glabra* leaves (E: Pond apple, S: Wel Aththa)	Aqueous extract	n.d
4.	*Annona squamosa* seeds (E: Custard apple, S: Seeni aththa)	Methanol crude extract	n.d.
5.	*Annon amuricata* (E:/S: Anona)	Aqueous extract	n.d.
6.	*Azadirachta indica* seed (E:Neem/S:Kohomba)	Aqueous extractions	n.d.
7.	*Azadirachta indica* seeds (E:Neem,S: Kohomba)	Aqueous extract	n.d
8.	*Azadirachta indica* seeds (E:Neem,S: Kohomba)	Aqueous extract	n.d
9.	*Azadirachta indica* (E:Neem, S: Kohomba)	Aqueous extract	n.d.
10.	*Azadirachta indica* (E: Neem, S: Kohomba)	Acetone crude extract	n.d.
11.	*Azadirachta indica* seed kernels (E: Neem, S: Kohomba)	Aqueous extract	Alkaloids, Tannins, Saponin, Coumarin
12.	*Calotropis gigantean* (E:, S:Wara)	Aqueous extract	n.d.
13.	*Celtis cinnamomea leaves* (E: Stinkwood, S: Gurenda)	Hot methanol crude extract	n.d.
14.	*Cestrum aurantiacum* (E: Orange Jessamine, S:)	Hot methanol crude extract	n.d.
15.	*Cestrum aurantiacum* (E: Orange Jessamine, S:)	Hot methanol crude extract	n.d.
16.	*Costus specious* (E: Crepe Ginger, S: Tebu)	Hot methanol crude extract	n.d.
17.	*Curcuma zedoaria tuber* (E: white turmeric, S: Haran kaha)	Hot methanol crude extract	n.d.
18.	*Curcuma zedoaria tuber* (E: white turmeric, S: Harankaha)	Hot methanol crude extract	n.d.

Sri Lanka

Target insect-pest	Insecticidal properties	Reference
Aphids	Insecticidal activity	(Nishantha *et al.*,2023)
Cabbage leaf-eating caterpillars, mites, and aphids	Insecticidal activity	(Nishantha *et al.*,2023)
The root-knot nematode (Meloidogyne incognita)	Nematicidal activity	(Lakmini & Amarasingh., 2018)
Epilachna beetles (Epilachna vigintioctopunctata)	antifeedant and lethal toxicity	(Karunaratne & Arukwatta, 2009)
Rice leaf folder (cnaphalocrocis medinalis)	Insecticidal activity	(Ekanayakel *et al.*, 2018)
Aphids, leaf miners, and pod borers in cowpea	Antifeedant	(Prasannath & Mahendran, 2013)
Hoppers (vector of Okra mosaic virus)	Less virus-infected plants	(Gururaj *et al.*, 2022)
Leaf-eating caterpillars of cabbage, knol-khol, Raddhish Aphids, leaf miners, thrips, mealybugs, and mites	Insecticidal activity	(Nishantha *et al.*, 2023)
Brown plant hopper (nilaparvata lugens),	Insecticidal activity	(Ekanayakel *et al.*, 2018)
Desert locust (Schistocerca gregaria)	Antifeedant	(Wickramananda *et al.*, 1998)
Hadda beetle (henosepilachna vigintioctopunctata f.)	antifeedant and lethal toxicity	(Thuvaraka & Pakeerathan, 2023)
Paddy bug (leptocorisaoratorius)	Insecticidal activity	(Ekanayakel *et al.*, 2018)
Groundnut aphid (Aphis craccivora)	Lethal toxicity	(Hewage *et al.*, 1997)
Diamondback moth (Plutella xylostella)	Low pupation and adult emergence antifeedant	(Hewage *et al.*, 1997)
Groundnut aphid (Aphis craccivora)	Lethal toxicity	(Hewage *et al.*, 1997)
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Diamondback moth (Plutella xylostella)	Low pupation and adult emergence Antifeedant	(Hewage *et al.*, 1997)

Table 1. List of liquid botanical crude extracts tested against insect pests of crops in

No.	Plant source	Extract type	Bioactive compounds
19.	*Dathura metel leaves* (E: Devil's Trumpet, S: Ela attana)	Ethyl acetate crude extract	tannins, terpenoids, phenols, saponins, flavonoids, alkaloids
20.	Garlic cloves + Ginger +Green Chilli	Aqueous extract	n.d.
21.	*Hortonia angustifolia* roots (E: S:)	Hot methanol crude extract	n.d.
22.	*Hortonia angustifolia* roots (E: S:)	Hot methanol crude extract	n.d.
23.	*Melia dubia* leaves (E:Malabar Neem, S: Lunumidella)	Methanol extract	n.d.
24.	*Ocimum sanctum* leaves (E: Holy basil, S: Maduruthala)	Ethanol crude extract	n.d
25.	*Ocimum gratissimum* (E: African basil, S: Gas thala)	Hot methanol crude extract	n.d.
26.	*Pleiospermium alatum* stem bark (E: Winged Naringi, S: Tumpath kurundu)	Hexane crude extract	n.d.
27.	*Pleiospermium alatum* stem bark (E: Winged Naringi, S: Tumpath kurundu)	Hexane crude extract	n.d.
28.	*Rhinacanthus nasutus* leaves (E: Snake jasmine, S: Aniththa)	Methanolic crude extract	n.d.
29.	*Tagetes erecta* leaves (E: Marigold, S: Daspethiya)	Ethyl acetate crude extract	tannins, terpenoids, phenols, saponins, flavonoids, alkaloids
30.	*Tagetes erecta* (E: Marigold, S: Daspethiya)	Methanolic crude extract	n.d.
31.	Zingiber zerumbet tuber (E: pinecone ginger, S:Wal inguru)	Hot methanol crude extract	n.d.

Pesticide formulations comprise two broad groups of chemicals: active ingredients and inert ingredients (Straw *et al.,* 2022). Active ingredients or botanical extracts aim to combat pests with their bioactive properties (Cox & Zeiss, 2022), and inert ingredients or additives are defined as the chemicals used to increase the effectiveness of the active ingredient. Inert help deliver the active ingredient to the target site, improving the product's efficiency and physical properties, etc. (Cox & Zeiss, 2022). Adjuvants, like surfactants, increase the effectiveness of pesticides in several ways (Castro *et al.,* 2013). The selection of materials to be utilised as inert ingredients in pesticide formulations is critical. Inert materials should ideally match the formulation's intended qualities, be low toxicity, economical, biodegradable, and require a simple manufacturing procedure (Yusoff et al., 2016).

Sri Lanka. (continued)

Target insect-pest	Insecticidal properties	Reference
Fall armyworm (spodoptera frugiperda)	Repellent activity	(Henagamage *et al.,* 2023)
Thrips (Scirtothrips dorsalis)	Repellent effect	(Rajeshkanna *et al.,* 2017)
Groundnut aphid (Aphis craccivora)	Lethal toxicity	(Hewage *et al.,* 1997)
Diamondback moth (Plutella xylostella)	Low pupation and adult emergence Antifeedant	(Hewage *et al.,* 1997)
Thrips, mealy bugs, Cabbage leaf-eating Caterpillars.	Insecticidal activity	(Kulawardhana *et al.,* 2018)
Cotton mealy bug (phenacoccus solenopsis)	Nymphal mortality	(Prishanthini & Vinobaba, 2014)
Groundnut aphid (Aphis craccivora)	Lethal toxicity	(Hewage *et al.,* 1997)
Groundnut aphid (Aphis craccivora)	Lethal toxicity	(Hewage *et al.,* 1997)
Diamondback moth (Plutella xylostella)	Low pupation Low adult emergence Antifeedant	(Hewage *et al.,* 1997)
Mealybugs, p. Marginatus,	Contact toxicity	(Bulugahapitiya *et al.,* 2021)
Fall armyworm (spodoptera frugiperda)	Antifeedent activity contact toxicity Repellent activity	(Henagamage *et al.,* 2023)
Fall armyworm (Spodoptera frugiperda)	Contact toxicity, Antifeedant activity, repellent activity	(Ranaweera *et al.,* 2020)
Groundnut aphid (Aphis craccivora)	Mortality	(Hewage *et al.,* 1997)

Nanoemulsion formulations

Nanoemulsions are a type of emulsion that can be described as a two-phase mixture of immiscible liquids, where the droplets are on the nanoscale and are stabilised by an amphiphilic surfactant (Barkat *et al.,* 2020; Jamali *et al.,* 2020). The particle size of nanoemulsion ranges from 50 to 500 nm (Erlina *et al.,* 2020). Nanotechnology-based pesticide formulations are being developed to improve active ingredient solubility, bioavailability, stability, and wettability during application, improving pest control and treatment efficacy (Luiz de Oliveira *et al.,* 2018; Mustafa & Hussein, 2020; Ravichandran *et al.,* 2022; Sharma *et al.,* 2020).

Advantages of plant-derived nanoemulsion insecticide formulations

Table 2 provides some examples of plant-derived nanoemulsion insecticide formulations. It includes botanical extracts, preparation methods, inert ingredients, properties, target pests and their efficacy as bioinsecticides.

Enhanced stability:

One of the key advantages of nanoemulsion formulations is their enhanced stability compared to traditional botanical extracts (Harwansh *et al.,* 2019). Nanoemulsions consist of small droplets that are stabilised by surfactants and co-surfactants, preventing the coalescence and separation of the formulation over time (Wilson *et al.,* 2022). This stability ensures the long-term effectiveness of the botanical extracts, allowing for extended shelf life and improved storage conditions. Stability and thermostability tests are carried out to test the enhanced stabilty of botanical nanoemulsion insecticidal formulations as prescribed by the Food and Agricultural Organization (FAO) as a standard evaluation of agrochemical products to show stability in the tropical climate (Norhayu *et al.,* 2015). Further, Zeta potential is used to determine the stability of nanoparticles (Lina *et al.,* 2020).

Improved bioavailability:

Nanoemulsion formulations significantly enhance the bioavailability of botanical extracts (Rahman *et al.,* 2020). The small droplet size of nanoemulsions provides a large surface area for interaction with pests or target organisms, facilitating efficient absorption and uptake. The reduced droplet size also allows for enhanced penetration through the cuticles of insects or plant tissues, ensuring the active compounds' better distribution and systemic action (Ravichandran *et al.,* 2022). This improved bioavailability increases pest and disease control effectiveness, requiring lower concentrations of botanical extracts to achieve desired outcomes. As an example in a contact bioassay, the nanoemulsion produced with Cupressus sempervirens essential oil induced a 100% adult mortality rate in a concentration of 10.0 μL cm^{-2} after 4 days of treatment, whereas 40 μL cm^{-2} of essential oil was required to kill 100% of Sitophilus oryzae (Almadiy *et al.,* 2023).

Targeted delivery:

Nanoemulsion formulations offer precise and targeted delivery of botanical extracts to pests or affected plant parts (Chhipa, 2019). The small droplet size allows for better dispersion and adhesion on plant surfaces, increasing the contact between the formulation and the target organisms. This targeted delivery approach enhances the selectivity and efficacy of botanical extracts, reducing the risk of environmental contamination and collateral damage to beneficial organisms.

Reduced environmental impact:

Botanical nanoemulsion formulations contribute to reducing environmental impact compared to conventional pesticides. The targeted delivery and enhanced bioavailability of nanoemulsion formulations minimise the amount of active ingredients required for effective pest and disease control, further reducing the environmental footprint (Jampílek *et al.,* 2019). The reduced application rates of nanoemulsion formulations result in a less residual impact on ecosystems, promoting sustainable agricultural practices (Almadiy *et al.,* 2023; Gomes *et al.,* 2023).

Nanoemulsion formulation techniques

Nanoemulsions can be prepared through different methods, including high-energy emulsification methods involving mechanical energy and low-energy emulsification methods involving chemical energy from the emulsion system (Figure 1) (Safaya & Rotliwala, 2020). In low-energy methods, the smaller droplets are formed when the system undergoes a phase inversion in response to changes in composition or temperature and passes through a state of low interfacial tension. In high-energy methods, mechanical tools such as ultrasonicators, microfluidisers, and high-pressure homogenisers are used to produce the disruptive forces (Kumar *et al.,* 2019). Low-energy methods are advantageous as they can be conducted at room temperature using simple stirring equipment, which is efficient and cost-effective (Azmi *et al.,* 2019).

The Emulsion Inversion Point (EIP) technique induces a phase inversion by water dilution, whereas the Phase Inversion Temperature (PIT) approach induces a phase inversion on the cooling of the mixture.

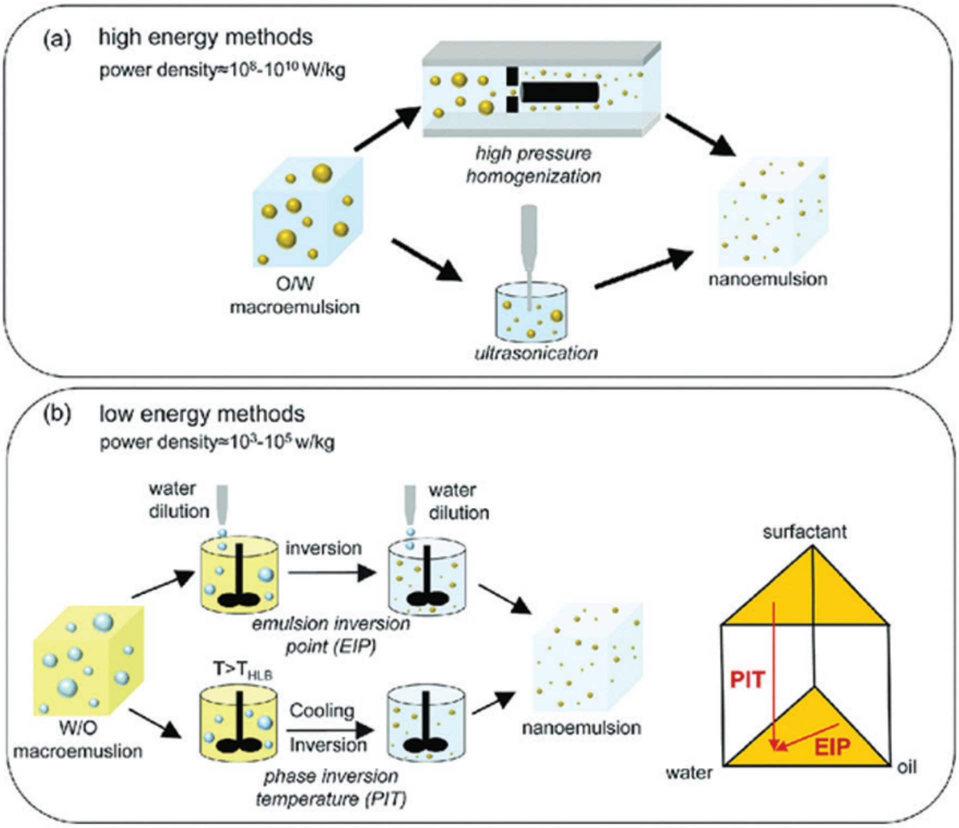

Figure 1. Overview of high-energy and low-energy methods for preparing O/W nanoemulsions. (Gupta *et al.,* 2016).

Table 2. Examples for plant-derived nanoemulsion insecticide formulations

No.	Plant extract (active compounds)	Preparation method	Inert ingredients	properties
1.	*Allium sativum* essential oil	self-emulsifying process followed by sonication	Tween 80 and distilled water	Particles size: 176.23 ± 0.9 nm Zeta potential –23.16 ± 0.29 mV Poly dispersity index:0.18
2.	*Allium sativa* clove essential oil	high-energy approach	Tween 80, Methanol, and distilled water	Particle size: < 100 nm.
3.	*Azadirachta indica* leaves essential oil	high-energy approach	Tween 80, Methanol and distilled water	Particle size: < 100 nm.
4.	*Azadirachta indica* essential oil (azadirachtin content: 2000 mg L^{-1})	Low-energy emulsification	Cymbopogon citratus essential oil, Prosopis juliflora extracts, Nonylphenol ethoxylate, Atlox 4916, glycerol, and double distilled water	Particle size: 25-50 nm Zeta potential: -30 mV) Poly-dispersive index: <0.3 Viscosity: 98.8 cPs
5.	*Boswellia sacra* essential oil	High-energy ultrasonication process	Tween 80 and water	Particle size: 41.30 nm Surface tension: 53.69, Viscosity: 4.76 cPs, Zeta potential: -10 mV, Polydispersity index: 0.26
6.	*Carlina acaulis* essential oil	High energy method (High-pressure homogenisation)	w/w of ethyl oleate Polysorbate 80.	Particle size: 110–140 nm Polydispersity index: 0.250 and 0.270.
7.	*Carlina acaulis* root essential oil	A high-energy method using a high-pressure homogeniser.	Polysorbate 80 and water	Particle size: 140 nm
8.	*Clidemia hirta* extract	spontaneous emulsification	Termul 1284, rapeseed oil and water	Particle size: 79 nm Surface tension: 35.41 mN.m-1 Zeta potential: -22.5 mV
9.	*Citrus sinensis* essential oil	High energy approach (ultrasonic immersion homogeniser)	Tween 80 and double distilled water	Particle size: 131.37 nm Zeta potential: −30 mV
10.	*Cupressus sempervirens* var. horizontalis essential oil	Low-energy emulsification method	Tween 80 and deionised water	Particle size: 67.8nm Polydispersity index: 0.18 pH: 6.1 Viscosity: 4.1 mPa.s

Purpose-Target insect pest	Bioactivities	Reference
Tuta absoluta	Toxic effect on eggs and larvae Repellent activity No lethal effect on the mirid predator Nesidiocoris tenuis, but significant reduction of progeny, no phytotoxicity on tomato plants	(Ricupero *et al.,*
Tetranychus urticae, Two-spotted spider mite	acaricidal activities	(Ismail *et al.,* 2022)
Tetranychus urticae, Two-spotted spider mite	acaricidal activities	(Ismail *et al.,* 2022)
Bemisia tabaci , Whitefly	Lethal toxicity	(Iqbal *et al.,* 2020)
E. insulana, spiny bollworm	Lethal toxicity to larvae, effect on larvae and pupae development	(Metayi *et al.,* 2022)
Meloidogyne incognita	Nematicidal activity	(Ntalli *et al.,* 2023)
Lobesia botrana, European grapevine moth	Lethal toxicity	(Benelli *et al.,* 2020)
Aphis (A.) gossypii	Repellent effect Lethal toxicity	(Roonjho et *al.,* 2022)
Tribolium confusum and *Cryptolestes ferrugineus*	The repellent effect, acute toxicity,	(Giunti *et al.,* 2019)
Sitophilus oryzae, rice weevil	Lethal toxicity to adults No adverse effect on earthworms (*Eisenia fetida*)	(Almadiy *et al.,* 2023)

Table 2. Examples for plant-derived nanoemulsion insecticide formulation. (continued)

No.	Plant extract (active compounds)	Preparation method	Inert ingredients	properties
11.	*Derris Elliptica* - Rotenone Extract	Spontaneous emulsification	Alkyl polyglucoside, organosillicone, dimethylamide, and deionised water	Particle size: 73.4 nm, Surface tension: 29 mN m^{-1}. .
12.	*Eruca sativa* Oil	Low-energy method	polyethylene glycol 400 and ethoxylated emulsifier	Particle size: 552.3 nm Polydispersity index: 0.653
13.	*Mentha piperita* (wild-type) essential oil	High-energy ultrasonication process	Tween 80 and autoclaved double-distilled water was	Particle size: 13.11 nm Zeta potential : -9.53 mV pH: 5.33
14.	*Piper aduncum* fruit extracts	Spontaneous emulsion method	Tween 80 Distilled water	Particle size:141.1 nm PDI: 0.106 Zeta potential: -21 mV
15.	*Piper aduncum* fruit extracts	Spontaneous emulsion method	Agristic, Distilled water	Particle size: 172.5 nm PDI: 0.092 Zeta potential: -25.9
16.	*Piper retrofractum* essential oil	Low-energy emulsification method by phase inversion	Tween-80 and water	particle size: <200 nm.
17.	*Simmondsia chinensis* Essential oil	High energy method (high-power ultra-sonicator)	Tween 20 and distilled water	Particle size: 185.4 nm
18.	*Tephrosia vogelii* extract	Low energy -Emulsion Inversion Point (EIP) method	Tween 80, Ethanol, and sterile distilled water	particle size 206.7 nm - 432.6 nm

**n,d.: not detected*

Optimisation strategies for botanical insecticide nanoemulsion formulations

Selection of surfactants and co-surfactants

Selecting appropriate surfactants and co-surfactants is crucial in formulating nanoemulsions. Surfactants help to reduce the interfacial tension between the oil and water phases, enabling the formation and stabilisation of small droplets (Kale & Deore, 2017). Co-surfactants enhance the solubilisation capacity of surfactants, leading to improved emulsification.

Optimisation of formulation parameters

Botanical nanoemulsion formulations comprise three basic components: the aqueous phase, carrier oil phase, and surfactant or surfactant mixture. Understanding the roles and effects of each component is crucial in formulating stable and high-quality nanoemulsions. The nanoemulsion's physiochemical properties, stability, and particle size are directly affected by the aqueous phase's ratios, concentrations, pH, polarity, and density

Purpose-Target insect pest	Bioactivities	Reference
Plutella xylostella ,DBM	Lethal toxicity	(Norhayu *et al.,* 2015)
Xanthogaleruca luteola, Elm Leaf Beetle	Antifeedant activity	(Mashhoor *et al.,* 2021)
(*Aphis gossypii*) Cotton aphid	Contact toxicity	(Heydari *et al.,* 2020)
C. pavonanai, cabbage cluster caterpillar	Lethal toxicity	(Erlina *et al.,* 2020)
C. pavonanai, cabbage cluster caterpillar	Lethal toxicity	(Erlina *et al.,* 2020)
Nilaparvata lugens, brown plant hopper	Lethal toxicity against nymphs	(Nuryanti *et al.,* 2020)
Agrotis ipsilon, black cutworm	Lethal toxicity	(Azab *et al.,* 2021)
Crocidolomia pavonana Large cabbage heart caterpillar	Lethal toxicity	(Lina *et al.,* 2020)

(Nirmala & Nagarajan, 2017). The oil phase is typically chosen from lipophilic or non-polar compounds (Kale & Deore, 2017), and its physiochemical features determine the emulsion's quality, characteristics, and stability (Nirmala & Nagarajan, 2017). Surfactants consist of polar or hydrophilic and non-polar or hydrophobic parts, crucial in supporting two immiscible fluids in an emulsion. They assist emulsification by reducing the surface interfacial tension between the dispersed and continuous phases (Kale & Deore, 2017). Proper oil and surfactant selection and their appropriate hydrophilic-lipophilic balance (HLB) value are critical for producing stable and acceptable nanoemulsions (Gadhave, 2014). The HLB scale has a scale of 0 to 20. Surfactants with HLB values ranging from 3.5 to 6.0 are more suited for forming W/O emulsions, whereas surfactants with HLB values ranging from 8 to 18 are better suited for producing O/W emulsions (Azman et al. 2019; Zheng *et al.,* 2015). The required HLB value of the oil phase and the emulsifier of the same HLB value increase stability and reduce emulsifier quantity (Gore *et al.,* 2021).

Characterisation of botanical insecticide nanoemulsion formulations:

Various criteria, such as particle size measurement, zeta potential, polydispersity index, pH, viscosity, surface tension, stability, thermodynamic stability, dispersibility, and shelf life, are used to characterise the botanical nanoemulsion formulations (Gurpreet & Singh, 2018). According to the Food and Agriculture Organization (FAO) standard for agrochemicals products, the thermostability of pesticide emulsion formulations testing is carried out under a tropical climate (Patil *et al.,* 2014). Nanoemulsions possess stability against creaming or sedimentation due to their small particle size (Ismail *et al.,* 2015). The zeta potential is an important measurement of particle behaviour and stability. It indicates probable particle dispersion characteristics. Particles with a zeta potential value between ±30 mV are considered physically stable (Gurpreet & Singh, 2018). The type of particles, concentration, water pH, and the type and concentrations of surfactants and oils impact Zeta potential (Shukla *et al.,* 2016). The polydispersity index determines the size range of particles in the system (Shukla *et al.,* 2016). The substance's acidity indicates that it will have high biological activity (Moustafa *et al.,* 2015). The optimum viscosity of a botanical pesticide formulation is required for long-term storage without sedimentation, complete transfer from container to spray tank, homogeneous dispersion for spray solution, and adhesion and reduction of run-off from target surfaces (Iqbal *et al.,* 2022). Lower surface tension improves wetting, spreading, and penetration into the applied surface of plants (Iqbal *et al.,* 2022).

Challenges and future perspectives of botanical nanoemulsion insecticide formulations in Sri Lanka

While botanical extracts are generally considered safe, conducting comprehensive toxicity studies to assess the potential risks of using nanoemulsion formulations and ensuring their safety for farmers, consumers, and the environment is crucial. Environmental fate and impact assessments should also be conducted to evaluate the long-term effects on non-target organisms, soil health, and water quality. However, Allium sativum essential oil nanoemulsion tested against *T. absoluta* in tomato has caused no lethal effect on the mirid predator Nesidiocoris tenuis. Still, the progeny was significantly reduced, and no phytotoxicity was reported on tomatoes (Ricupero *et al.,* 2022). *Cupressus sempervirens var. horizontalis* essential oil nanoemulsion, which effectively manages *Sitophilus oryzae*, rice weevil, has not caused any adverse effect on earthworms (*Eisenia fetida*) (Almadiy *et al.,* 2023). Developing standardised protocols for safety assessment and environmental risk evaluation will further support the responsible and sustainable use of nanoemulsion formulations. Collaborative research and development efforts are essential to overcome the challenges and realise the full potential of botanical nanoemulsion insecticide formulations in Sri Lankan agriculture. Collaboration between universities, research institutions, private sector other government organisations such as the Sri Lanka Institute of Nano Technology (SLINTEC) can foster innovation, facilitate knowledge exchange, and accelerate the development of effective and practical nanoemulsion formulations. These collaborative efforts can lead to the development of optimised botanical insecticide formulations, efficient manufacturing processes, and customised solutions tailored to the specific needs of Sri Lankan agriculture.

Conclusions

Botanical extracts hold great promise as environmentally sustainable alternatives to synthetic pesticides in agriculture. Still, poor stability and low water solubility have limited their practical application. Locally produced, commercial formulations of botanical insecticides are still limited in Sri Lanka, indicating the need for further research and practical implementation. This review highlights the potential botanicals in Sri Lanka that can be developed into nanoemulsion formulations, drawing lessons from examples in other countries. With their small droplet size and surface properties, nanoemulsions enhance botanical extracts' bioavailability, shelf life, stability, and effectiveness. Formulating effective nanoemulsions involves selecting appropriate components and their concentrations, optimising formulation parameters, and characterisation. The successful adoption of botanical-based nanoemulsion formulations for pest management in Sri Lanka depends on continued research, development, and application. This will promote sustainable agriculture and safer environmental and human health practices.

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