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Review article

Biocontrol agents and their potential use as nano biopesticides to control the tea red spider mite (Oligonychus coffeae): A comprehensive review

Jahid Hasan Shourove [a,*], Fariha Chowdhury Meem [a], Razia Sultana Chowdhury [a], Shamima Akther Eti [b], Mitu Samaddar [a]

[a] *Food Engineering and Tea Technology, Shahjalal University of Science and Technology, Sylhet, Bangladesh*
[b] *Bangladesh Council of Scientific and Industrial Research, Dhaka, Bangladesh*

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ABSTRACT

Tea red spider mite (TRSM), *Oligonychus coffeae* Nietner, is one of the major pests that cause considerable crop losses in all tea-growing countries. TRSM management often involves the use of multiple chemical pesticides that are linked to human health risks and environmental pollution. Considering these critical issues, employing biocontrol agents is a potential green approach that may replace synthetic pesticides. This review study aims to discuss the efficacy of plant extracts, entomopathogenic microorganisms, and predators in controlling TRSM. This study includes 44 botanical extracts, 14 microbial species, and 8 potential predators used to control TRSM, along with their respective modes of action. Most of the botanical extracts have ovicidal, adulticidal, and larvicidal activity, ranging from 80 to 100 %, attributed to bioactive compounds such as phenols, alcohols, alkaloids, tannins, and other secondary metabolites. Among microbial pesticides, *Purpureocillium lilacinum, Metarhizium robertsii, Aspergillus niger, Pseudomonas fluorescens, and Pseudomonas putida* are highly effective against TRSM without causing any harm to the nontarget beneficial insects. Besides, some predators, including green lacewings, ladybirds, and phytoseiid mites have the potential to control TRSM. Employing these biocontrol agents simultaneously in tea plantations could be more effective in preventing TRSM. Nevertheless, their high biodegradability rate, uneven distribution, and uncontrolled release pose challenges for large-scale field applications. This study also explores how nanotechnology can enhance sustainability by addressing the limitations of biopesticides in field conditions. This review study could contribute to the search for potential biocontrol agents and the development of commercial nano biopesticides to control TRSM.

1. Introduction

Tea is a healthy and popular drink worldwide, with beneficial properties such as antioxidants, anti-inflammatory, anti-obesity, and anti-cancer activities [1]. During the COVID-19 pandemic, homemade tea gained popularity as an immunity booster and sore throat reliever. It is a good source of phytochemicals, including polyphenols, flavonoids, and vitamins, with antiviral capacity [2].

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* Corresponding author.
E-mail address: shourove-fet@sust.edu (J.H. Shourove).

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Epigallocatechin gallate (EGCG) and theaflavins, including theaflavin (TF1), theaflavin-3-gallate (TF2A), theaflavin-3′-gallate (TF2B), and theaflavin-3,3′-digallate (TF3), are polyphenols abundant in tea that can inhibit viruses such as the hepatitis C virus, Zika virus, chikungunya, influenza A, dengue, Ebola and rotavirus [3]. It also has the potential to inhibit the SARS-CoV-2 virus and works as a therapeutic agent against COVID-19 [3,4]. Over the last decades, there has been a 3.5 % global growth in tea consumption [5]. To ensure the long-term sustainability of the tea industry, it must overcome a variety of obstacles [5]. However, one of the major threats to tea-growing countries is tea pests, which result in a decrease in net productivity by approximately 20 % [6].

The tea red spider mite (TRSM), *Oligonychus coffeae* Nietner (Acari: Tetranychidae), is a major sucking pest of tea found in almost all tea-growing areas. Infestation of this pest leads to a significant loss in tea yield, reaching as high as 46 % [7,8]. Control of TRSM has received substantial consideration from entomologists and acarologists from the very beginning. Several types of chemical pesticides, including sulfur formulations-tedion, kelthane, akar 338, malathion, lime sulfur, and the organophosphorus compounds-rogor and ekatin, are already being used in tea plantations [9,10]. Recently, propargite, abamectin, bifenthrin, chlorfenapyr, dicofol, ethion, fenazaquin, fenpyroximate, fenpropathrin, hexythiazox, and spiromesifen have been used to control TRSM [8,11,12]. These chemical pesticides affect the safety of made tea by leaving behind pesticide residues. Additionally, the sulfur formulation gives the tea a tainted flavor [9,11].

However, the incidence of pesticide residues in made tea is becoming a growing public health concern due to its potential to cause various diseases such as Alzheimer's or Parkinson's disease, birth defects, cancer, diabetes, infertility, and thyroid disorders when consumed [13,14]. These residues may come from the chemical pesticides widely used in tea plantation fields to combat harmful pests. Synthetic pesticides require a long time to decompose in the atmosphere, leading to pesticide residues in plucked leaves [13]. International organizations, including the United States Environmental Protection Agency (USEPA), the Codex Alimentarius Commission (CAC), the Commission of European Communities (CEC), and the Food and Agricultural Organization (FAO), have set maximum residue limits (MRLs) for chemical pesticides in tea [15,16]. Therefore, producers must comply with international pesticide residue laws to reduce the ecological and health hazards from pesticide contamination. Despite the recent development of adenosine triphosphate (ATP) disruptors for insect pest control, neurotoxic pesticides are still widely used. This practice has led to severe health problems in humans and non-targeted animals and environmental pollution [17]. Moreover, the extensive use of synthetic pesticides can lead to the extinction of beneficial insects and pollinators [18]. As tea is the most widely consumed beverage worldwide, it is crucial to avoid chemical hazards in tea production [1,19].

Additionally, TRSM has already developed resistance to many synthetic pesticides due to its high reproductive rate, numerous annual generations, and frequent exposure [8,20]. Therefore, sustainable tea crop production is necessary to control TRSM using environmentally friendly alternatives to traditional chemical pesticides [21]. Good Agricultural Practices (GAP) promote such alternative control approaches by substantially reducing chemical usage and increasing efforts to discover biocontrol agents. The current integrated pest management strategy for tea crops emphasizes the employment of biocontrol agents such as plant extracts, microbial species, and predators as non-toxic alternatives to chemical pesticides for dealing with the most problematic insects and mites [22]. Several studies have already examined the potency of such biocontrol agents to control TRSM [23–28].

Biocontrol agents are comparatively broader terms that are generally preferred by the European Union (EU) regulations rather than biopesticides [29]. Biocontrol agents are divided into four groups: macrobial (parasitoids, predators, entomopathogenic nematodes), microbial (bacteria, viruses, soil microorganisms), natural products (natural and biochemical products), and semiochemicals (pheromones) [30]. However, biopesticide is a popular term in the United States regulatory framework which classifies it as microbial pesticides, plant-incorporated protectants, and biochemical pesticides [31]. Nowadays, the production and application of biopesticides in agriculture have slowly evolved into a trend as people pay increasing attention to environmental quality [32]. Biopesticides are gaining popularity in pest management due to their low environmental impact, specificity to pests, high effectiveness in small quantities, and rapid decomposition [33,34]. Yet, farmers may only use biopesticides to a limited extent because they lack information on their specificity, potency, action speed, and mode of action [35]. Moreover, the shorter shelf life, the requirement for higher dosages, and a higher degradability rate due to interactions with environmental factors are becoming major obstacles in the field applications of biopesticides [36]. Despite their numerous potentialities, biopesticides must be developed by addressing such issues to achieve sustainability [37]. In that regard, nanotechnology is the most effective approach for overcoming these hurdles and complementing traditional environmental remediation strategies [37,38].

Previous studies have highlighted some common management techniques for the TRSM [39] and other arthropod pests in tea [40]. However, none of these publications have identified the most efficient biocontrol agents specifically targeting TRSM. Hence, their findings are not comparable, making it difficult to draw measurable conclusions. Moreover, none of the studies included strategies to enhance the efficacy of biocontrol agents under field conditions. To address this gap, the current study focuses on critically assessing the efficacy of biocontrol agents, as well as exploring potential measures to enhance their functionality through the application of nanotechnology. As biocontrol agents have several limitations, it has become crucial to find more effective ones for sustainable tea cultivation. Therefore, this review highlights the efficacy of biocontrol agents and suggests further directions to explore their use as nano biopesticides to effectively control TRSM.

2. Red spider mite in tea

Tea (*Camellia sinensis* (L.) Kuntze) is a deep-rooted, evergreen, and perennial crop where intermittent light is provided by interplanting shade trees. In mature and old tea plantations, the bushes become dense, providing a suitable breeding habitat for tea pests [41,42]. Worldwide, tea plantations are anticipated to be infested by over 1000 species of arthropods, serving as pests, seasonal visitors, predators, and parasitoids [9]. Among the various pests, mites are the most prevalent in tea-growing countries, with over 12 documented species, the most notable of which is the TRSM. It is widely distributed in India, Bangladesh, Sri Lanka, Taiwan, Burundi, Kenya, Malawi, Uganda, and Zimbabwe. TRSM is also known as the red coffee mite, coffee small mite, and tea star scream [39].

2.1. *Life cycle of TRSM*

The life cycle of TRSM comprises five stages: egg, larva, protonymph, deutonymph, and adult, with periods of dormancy between active phases. It has a relatively short lifespan, averaging around 20–30 days [39]. Fig. 1 represents the different growth stages of TRSM.

During its complete lifecycle, the mite spends 56 % of its time as an adult, 24 % as an egg, and 20 % as a juvenile [43]. The egg is characterized by its light orange color, smooth texture, ovoid or spherical shape, and flattened lower surface with a slight indentation on the exposed top side [44,45]. Female mites lay eggs at regular intervals on the leaf surface, primarily along the midrib and veins. Weather conditions such as mean air temperature, relative humidity, rainfall, and tea clone type, can affect egg production, hatch rate, incubation period, longevity, and development of TRSM [46,47]. Hundreds of spider mites and eggs can be found on each tea leaf's upper and lower surfaces [48]. The larva is almost spherical and has six legs, while the deutonymph is larger than the protonymph and can differentiate between the sexes [39]. The adult stage follows the third quiescent stage. During the cropping season (March–October), TRSM exhibits the highest fecundity, shortest incubation time, shortest life cycle, and largest female population, with a sex ratio of 1:1.2 [48].

2.2. *Importance of TRSM management*

TRSM is known to inflict substantial harm to tea plants at several stages of development, including larvae, nymphs, and adults. They feed by repeatedly puncturing the epidermis of tea leaves with their chelicerae and sucking up the sap [49]. This feeding process leaves small reddish-brown indentations on the upper surface of mature leaves, which may turn red under excessive stress [20]. TRSM can be found on both sides of the tea leaf; however, they are typically found on the upper surface of mature tea leaves, especially along the midrib and leaf margins [50]. TRSM Infestation impairs the photosynthetic activity of tea leaves, leading to wilting. The dry and curled leaves gradually lose their function and defoliate. Severe defoliation and reduced photosynthetic activity can impede shoot growth [51]. Plants with low root starch reserves after pruning are more susceptible to TRSM-induced stress.

During severe outbreaks such as droughts, TRSM affects both young and mature leaves, although it typically targets mature leaves [52]. Drought exacerbates the attack of TRSM on tea, which can be highly detrimental to young plants and weak bushes [52]. During the drought season (March–May), significant damage is observed in tea plantations, especially those that are not shaded [52]. Severe TRSM infestation, followed by drought, can cause 5–100 % yield loss depending on the degree of infestation [20,49]. The TRSM infestation has increased during the last decade due to the rise in temperature, humidity, erratic rainfall, and intermittent sunshine [53]. According to several researchers, attention must be given to TRSM as it is ubiquitous in tea-growing regions and is responsible for 17–46 % of crop losses [8,46,49]. Concurrent infestation by the red spider mite and tea mosquito bug (*Helopeltis theivora* Waterhouse) can cause significant damage to the tea crop, resulting in substantial losses in yield and quality. In some cases, the losses can be as high as 80 % [16].

3. Biocontrol agents used to control TRSM

A significant reduction in the use of chemical pesticides is one of the goals of the EU's Farm to Fork strategy, which outlines the transition towards a sustainable food system and commits to reducing the use of chemical pesticides by 50 % by 2030 [54]. To achieve this goal, biological control agents such as biopesticides and predators could be used as sustainable and eco-friendly tools to manage TRSM. According to the USEPA, biopesticides are a category of insecticides manufactured from naturally occurring components, including minerals, plants, bacteria, animals, and other living organisms that may eliminate agricultural pests [31]. Among these, botanical extracts and microorganisms are potential biopesticides against TRSM mitigation (Tables 1–3).

3.1. *Plant-based biopesticides to control TRSM*

Secondary metabolites, often known as phytochemicals, botanicals, or plant extracts, are produced by plants to defend against pests and adverse climatic conditions [76]. Recent studies have shown that botanical extracts can effectively protect plants from pests without causing harm to the environment or mammals [23,25,41]. They exhibit various potentials, including toxicity, repellency, antifeedant activity, and growth regulatory actions against pests of agricultural relevance, making them a desirable alternative to chemical pesticides [41,76]. Depending on the type of phytochemical and pest, the modes of action may involve protein denaturation, repulsion, or growth inhibition [33]. The phenols, alcohols, alkaloids, tannins, and other secondary metabolites present in botanical extracts can be toxic to the organelles, cell walls, and membranes of pests. These metabolites also inhibit the production of crucial enzymes, DNA, and protein synthesis. Botanical pesticides possess pesticidal properties that inhibit egg hatching and decrease populations of TRSM. Phytochemicals such as piperamides, acetogenins, thiophenes, and limonoids are particularly effective against mites [41]. Botanical pesticides constitute a mere 5 % of the biopesticide market, representing only 8 % of the global pesticide market [77]. Table 1 represents the recent findings on the pesticidal potency of several botanical extracts against TRSM.

3.1.1. Preparation of Plant extracts

Active ingredients (AIs) are generally extracted from various parts of plants, including leaves, succulent stems, seeds, and bulbs. Briefly, the plant samples are dried in the shade at room temperature and then powdered using an electric blender. The dried powders are soaked overnight in water and other solvents where the solid-to-solvent ratio is maintained at 1:10 to 1:20 as required. The solution is later extracted and filtered using a double-layer muslin cloth [23]. The resulting residue is dissolved again in a solvent to create a stock solution. Subsequently, a series of dilutions is prepared from the 100 % stock solution using the serial dilution method [64]. Additionally, 0.5 mL of a neutral surfactant (IG SURF 2115) is also added [10,24,55]. From this stock solution, the spray fluid is prepared at various concentrations for conducting bioefficacy studies [64]. However, the concentration of the solvent, type of solvent, particle size, and extraction time may affect the pesticidal efficacy of plant extracts [78]. The solvent should be completely evaporated using a vacuum rotary evaporator at a bath temperature below 50 °C [64] to eliminate the solvent's impact on pest mortality [78].

3.1.2. Acaricidal activity of pesticidal plant extracts in laboratory studies

Table 1 represents the acaricidal activity of some plant extracts under laboratory studies. The neem (*Azadirachta indica* A. Juss) extract is a natural systemic pesticide that can provide plants with long-term protection against TRSM [10,24,79,80]. Aqueous extract of neem kernel (NKAE) resulted in 72.33 %–92 % mortality in adult TRSM [10,24,55] and 95.2 % mortality in the nymph. The mortality rate was found to increase with concentration and the treatment period (Hour After Treatment, HAT) [10,24,55]. Meliacarpins containing Ghora neem (*Melia azedarach* L.) seed extracts (10 %) also exerted 90.6 % TRSM mortality [26]. Another triterpenoid, toosendanin, is a substance reported to be a stomach poison for chewing pests [26]. However, the acaricidal potency significantly increased while using NKAE with mesquite (*Prosopis juliflora* (Sw.) DC.) seed powder. The adult RSM mortality reached up to 100 % due to the synergistic effects [23]. The prominent acaricidal activity may result from the presence of AIs including proto-limonoids, limonoids, tetranor-triterpenoids, pentanor-triterpenoids, hexanor-triterpenoids, and several nonterpenoids in NKAE. Triterpenoids such as azadirachtin, azadirachtin B, salannin, and nimbin, can prevent the normal development and feeding of TRSM [81]. Moreover, *P. juliflora* seed extracts contain high levels of piperidine alkaloids, particularly juliprosopine which exhibits the highest toxicity on TRSM along with azadirachtin [82]. In a laboratory study, pure azadirachtin (0.15 % EC) exhibited 100 % mortality of TRSM within 96 h [25]. Azadirachtin is a registered biopesticide in the United States as a general-use pesticide with a toxicological class EPA of IV (relatively non-toxic) [31]. Moreover, EU regulation No 540/2011 also approved it as a nontoxic active substance for plant protection [83].

Oil derived from karanja (*Pongamia pinnata* (L.) Pierre) seed contains around 5–6% flavonoids, principally karanjin, and pongamol, which are responsible for its pesticidal efficacy (100 %) against TRSM [84]. They have insect antifeedant, repellent, and growth inhibition capacities [85]. Moreover, aqueous extract of wild sunflower (*Helianthus* spp.) leaf [68]*, bracken fern (Pteridium aquilinum* (L.) Kuhn) leaflet [69], Indian mulberry (*Morinda tinctoria* Roxb) leaf [70], and garlic (*Allium sativum* L.) bulb [24] has been found to exhibit 100 % acaricidal activity against adult TRSM. Bur weed, *Xanthium strumarium* L., had also good acaricidal activity (91.8 %) [59].

Lantana (*Lantana camara* L.) plants contain miticidal flavonoids, triterpenoids, and alkaloids like lantanine [86]. Lantana leaf

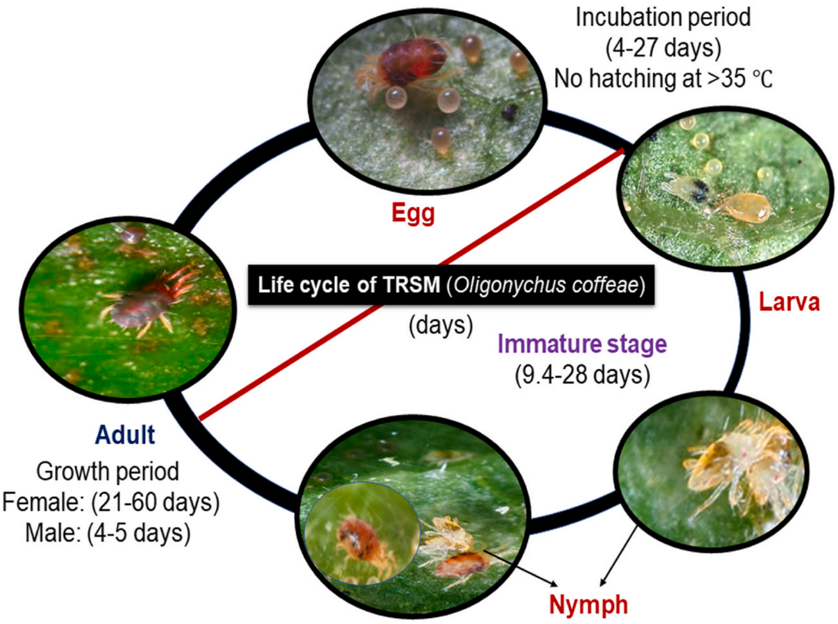

Fig. 1. Life cycle of tea red spider mite (*Oligonychus coffeae* Nietner). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Application of different plant-based extracts as biopesticides in laboratory and field levels to control TRSM.

Sl. no	Plant		Part	Extract concentration	Laboratory study				Field study		Reference
	Common name	Scientific name			Mortality			HAT			
					Egg	Nymph	Adult		Population reduction	Treatment period	
1.	Neem	*Azadirachta indica* (Sapindales: Meliaceae)	Kernel	2.5 % (aqueous)	50 %	–	–	12 days	–	–	[23]
			Kernel	5 % (aqueous)	92 %	–	84 %	96	–	–	[24]
			Kernel	5 % (aqueous)	92.9 %	–	72.33 %	72	–	–	[10]
			Kernel	5 % (aqueous)	25.2 %	–	86 %	96	–	–	[55]
			Kernel	10 % (aqueous)	65 %	95.2 %	92 %	72	69.8 %	2 weeks	[56]
	Neem + Mesquite	*Azadirachta indica* +*Prosopis juliflora* (Fabales: Fabaceae)	Neem kernel: Mesquite seed (1:1)	5 % (aqueous) 10 % (aqueous)	99 %	–	93 % 100 %	72 48	– –	– –	[23]
	Neem based pesticide- Azter		Azadirachtin (0.15 % EC)	2250 mL/ha	73.55 %	–	100 %	96	–	–	[25]
2.	Ghora-neem/ chinaberry tree	*Melia azedarach*	Seed	10 % (aqueous)	65 %	–	90.6 %	72	–	–	[26]
3.	Pongam/karanja	*Pongamia pinnata* (Fabales: Fabaceae)	Kernel	5 % (aqueous)	70 %	–	100 %	72	–	–	[24]
4.	Garlic	*Allium sativum* (Asparagales: Amaryllidaceae)	Bulbs	5 % (aqueous)	50 %	–	100 %	72	–	–	[24]
			Bulbs	–	–	LC_{50}: 2.92 mg/mL	LC_{50}: 4.32 mg/mL	72	–	–	[57]
				Garlic Oil	LC_{50}: 312.40 ppm	–	LC_{50}: 13.628 ppm	–	–	–	[58]
5.	Nishinda	*Vitex negundo* (Lamiales: Lamiaceae)	Leaf	–		LC_{50}: 2.86 mg/mL	LC_{50}: 4.08 mg/mL	72	–	–	[57]
6.	Sky flower	*Duranta erecta* (Lamiales: Verbenaceae)	Leaves and succulent stems	10 % (aqueous)	44.44 %	–	100 %	72	75.1 %	4 weeks	[41]
7.	Bur weed/Agora	*Xanthium strumarium* (Asterales: Asteraceae)	Leaves and succulent stems	10 % (aqueous)	87.09 %	–	91.8 %	72	90.2 %	14 days	[59]
			Aerial part	10 % (aqueous)	–	–	89.66 %	72	87.50 %	7 days	[60]
8.	Sweet flag/Boch	*Acorus calamus (Acorales: Acoraceae)*	Rhizome	10 % (aqueous)	70.62 %	–	88.7	72	86.4 %	14 days	[59]
9.	Smartweed/ Knotweed/ Bishkatali	*Persicaria hydropiper* (Caryophyllales: Polygonaceae)	Leaves and succulent stems	10 % (aqueous)	30.86 %	–	84.2	72	64.7 %	14 days	[59]
			Aerial parts	10 % (aqueous)	–	–	81.24 %	72	78.18 %	14 days	[60]
10.	Bhat/hill glory bower	*Clerodendron infortunatum* (Lamiales: Lamiaceae)	Leaves and succulent stems	10 % (aqueous)	20.58 %	–	100 %	72	100 %	7 days	[59]
			Leaves and succulent stems	10 % (aqueous)		–	–	–	81.63–90.02 %	4 weeks	[61]
				8 % (methanol)	69.33 %	–	–	–	93.40 %	4 weeks	[62]
				8 % (petroleum ether)	73.33 %	–	–	–	94.03 %	4 weeks	[62]
				8 % (acetone)	87.5 %	–	–	–	92.01 %	4 weeks	[62]
11.	Orange jasmine/ Kamini	*Murraya paniculata* (Sapindales: Rutaceae)	Leaf	10 % (aqueous)	48.5 %	–	67 %	72	–	–	[49]
12.	Sickle senna	*Senna tora* (Fabales: Fabaceae)	Leaf	10 % (aqueous)	34.15 %	–	52 %	72	–	–	[49]
13.	Opulentum fern	*Amphineuron opulentum*	Leaf	10 % (aqueous)	57.4 %	–	70 %	72	–	–	[49]

(*continued on next page*)

Table 1 (*continued*)

Sl. no	Plant		Part	Extract concentration	Laboratory study				Field study		Reference
	Common name	Scientific name			Mortality			HAT			
					Egg	Nymph	Adult		Population reduction	Treatment period	
14.	Tree marigold	*Tithonia diversifolia* (Asterales: Asteraceae)	Leaf	10 % (aqueous)	66.71 %	–	82 %	72	–	–	[49]
15.	Ringworm cassia/ dadmardan	*Senna alata* (Fabales: Fabaceae)	Leaf	10 % (aqueous)	58.4 %	–	81 %	72	–	–	[49]
16.	Datura	*Datura metel* (Solanales: Solanaceae)	Leaves and fruits	10 % (aqueous)	–	–	69.94 %	72	63.80 %	7 days	[60]
17.	Lantana	*Lantana camara* (Lamiales: Verbenaceae)	Leaves and twigs Leaves	10 % (aqueous) –	– 0.0–15.70 %	– –	79.31 % 23.30–95.20 %	72	75.07 % –	7 days –	[60] [16]
18.	Mahogoni	*Swietenia mahagoni* (Sapindales: Meliaceae)	Leaves and seeds	10 % (aqueous)		–	86.21 %	72	82.70 %	7 days	[60]
19.	Marotti/ Hydnocarpus	*Hydnocarpus pentandrus* (Malpighiales: Achariaceae)	Seed oil	5 mL/L	100 %	–	87 %	96	–	–	[63]
20.	Paradise tree	*Simarouba glauca* (Sapindales: Simaroubaceae)	Seed oil	5 mL/L	90.25 %	–	86 %	96	–	–	[63]
21.	Allamanda/golden trumpet	*Allamanda catharitica* (Gentianales: Apocynaceae)	Leaves	5 % (aqueous)	20 %	–	100 %	96	–	–	[55]
22.	Horse weed	*Erigeron bonariensis* (Asterales: Asteraceae)	leaves	5 % (aqueous)	15.2 %	–	80 %	96	–	–	[55]
23.	Floss flower	*Ageratum houstonianum* (Asterales: Asteraceae)	Leaves	5 % (aqueous)	0 %	–	54.0 %	96	–	–	[55]
24.	Spanish needle	*Bidens pilosa* (Asterales: Asteraceae)	Flowers	5 % (aqueous)	0 %	–	62.0 %	96	–	–	[55]
25.	Horse tail	*Casuarina equisetifolia (Fagales: Casuarinaceae)*	Leaves and flowers	5 % (aqueous)	0 %	–	16.0 %	96	–	–	[55]
26.	Quickstick/mata ratón	*Gliricidia sepium* (Fabales: Fabaceae)	–	5 % (aqueous)	21.2 %	–	70.0 %	96	–	–	[55]
27.	Wood apple	*Aegle marmelos* (Sapindales: Rutaceae)	Leaves	5 % (methanol) 10 % (methanol)		– –	– –	– –	43.8–66.0 % 59.4–85.0 %	–	[41]
			Leaves	10 % (95 % Methanol)	LC_{50}: 3025.74 ppm	LC_{50}: 1027.9 ppm	LC_{50}: 931.46 ppm	24	85.0 %	3 weeks	[64]
				10 % (95 % Ethanol)	LC_{50}: 4804.72 ppm	LC_{50}: 1140.17 ppm	LC_{50}: 1506.7 ppm	24	–	–	
28.	Ten-petal linostoma	*Linostoma decundrum* (Malvales: Thymelaeaceae)	Leaf	1 % (acetone)		–		–	87 %	10 days	[65]
29.	Tita phool	*Phlogacanthus tubiflorus* (Lamiales: Acanthaceae)	Leaf	1 % (acetone)		–		–	69 %	10 days	[65]
30.	Indian soapberry/ washnut	*Sapindus mukorossi* (Sapindales: Sapindaceae)	Fruits	8 % (aqueous)	LC_{50}: 5.47 %	–	LC_{50}: 2.12 %	–	83.37 %	3 weeks	[66]
31.	Red Nongmangkha	*Phlogacanthus thyrsiformis* (Lamiales: Acanthaceae)	Leaves	8 % (aqueous)	LC_{50}: 1.03 %	–	LC_{50}: 4.46 %	–	71.25 %	3 weeks	[66]
32.	Night Blooming Jasmine	*Nyctanthes arbor-tristis* (Lamiales: Oleaceae)	Leaves	8 % (aqueous)	LC_{50}: 4.75 %	–	LC_{50}: 2.962	–	64.94 %	2 weeks	[66]
33.	Clove plant	*Syzygium aromaticum* (Myrtales: Myrtaceae)	Clove oil	1.5 % (aqueous)	30 %	– –	73.33 % 98.54 %	72 120	– –	– –	[67]

(*continued on next page*)

Table 1 (*continued*)

Sl. no	Plant		Part	Extract concentration	Laboratory study				Field study		Reference
	Common name	Scientific name			Mortality			HAT			
					Egg	Nymph	Adult		Population reduction	Treatment period	
34.	Jatropha/physic nut	*Jatropha curcas* (Malpighiales: Euphorbiaceae)	Jatropha oil		LC_{50}: 118.54 ppm	–	LC_{50}: 12.42 ppm	–	–	–	[58]
35.	Mugwort	*Artemisia vulgaris (Asterales: Asteraceae)*	Leaves and stems	10 % (aqueous)	–	–	60–78 %	72	–	–	[68]
36.	Wild sunflower	*Helianthus* sp. (Asterales: Asteraceae)	Leaves	2–10 % (aqueous)	–	–	60–100 %	72	–	–	[68]
37.	Forked fern	*Dicranopteris linearis* (Gleicheniales: Gleicheniaceae)	Leaflets	5 %	–	–	80.0 ± 3.1 %	96	52.03 %	3 weeks	[69]
38.	Bracken fern	*Pteridium aquilinum* (Polypodiales: Dennstaedtiaceae)	Leaflets	5 %	–	–	100 %	96	56.69 %	3 weeks	[69]
39.	Swamp shield-fern	*Cyclosorus interruptus* (Polypodiale: Aspleniineae)	Leaflets	5 %	–	–	62.0 ± 5.8 %	96	–	–	[69]
40.	Fireweed	*Crassocephalum crepidioides* (Asterales: Asteraceae)	Leaves and flowers	5 % (aqueous)	100 %	–	0 %	96	–	–	[55]
41.	Gliricidia	*Gliricidia maculate* (Fabales: Fabaceae)	Leaves	2.5–7.5 % (aqueous)	24–66 %	–	40–74 %	–	–	–	[70]
42.	Indian mulberry	*Morinda tinctoria* (Gentianales: Rubiaceae)	Leaves	2.5–7.5 % (aqueous)	34–76 %	–	54–100 %	–	–	–	[70]
43.	Common Basil	*Ocimum basilicum* (Lamiales: Lamiaceae)	Leaves and flowers	5 % (aqueous)	100 %	–	40 %	96	–	–	[55]
44.	Black- or chebulic myrobalan	*Terminalia chebula* (Myrtales: Combretaceae)	Pericarp of the fruits	4–6% (aqueous)	–	–	52.4–90.0 %	24	89.2–100 %	1 week	[39]

*Sl = serial number, HAT= Hours after Treatment.

extract has exhibited 23–95 % adult TRSM mortality [16], whereas extract of orange jasmine leaf *(Murraya paniculata* (L.) Jack) caused 67 % mortality at 10 g/L concentration [49]. The major phytochemicals in the *M. paniculata* essential oil are monoterpenes and sesquiterpenes. The nerolidol is the leading AI in this oil makes it more effective at penetrating the skin [87]. The horseweed *Erigeron bonariensis* L. extract causes 80 % TRSM mortality [55]. Golden trumpet (*Allamanda catharitica* L.) extract resulted in 100 % mortality of adult TRSM at 5 % concentration after 96 h of observation, which may be due to a high amount of saponins in the extract [55,88,89].

The aqueous extract of *Clerodendron infortunatum* L. leaf has been found to effectively control TRSM, with a mortality rate of up to 100 % in adult TRSM [59,61]. It contains some chemical compounds such as clerodin, lupane, clerodone, uncinatone, and pectolinarigenin, having acaricidal potency [90]. Therefore, TRSM adults had an olfactory, gustatory, or contact response to that extract [18]. The calamus, found in the rhizomes of the sweet flag (*Acorus calamus* L.), is a source of active chemical substances, including tannins and saponins. It causes adult TRSM mortality (60–88 %) [16]. Similarly, the seed oil of Marotti *(Hydnocarpus pentandrus* (Buch.-Ham.) Oken) resulted in 87 % adult TRSM mortality [63], with hydnocarpic acid and chaulmoogric acid identified as the active ingredients [91]. Notably, aromatic flavonoids and free fatty acids in *H. pentandrus* oil act as effective agents against the rice weevil (*Sitophilus oryzae*) [92].

The mortality rate of the TRSM was increased with the concentration of sky flower *(Duranta erecta* L.) extract and treatment period. After 24 h of exposure to 6, 8, and 10 g/L extract, 30–86.67 % of adults died, rising to 76–100 % after 72 h [41]. It contains steroids, triterpenes, iridoids, diterpenoids, flavonoids, triterpene saponins, and saponins, all of which have insecticidal properties [41]. Wood apple (*Aegle marmelos* (L.) Corrêa) plant oil contains β-terpinyl acetate, 5-Isopropenyl-2-methyl-7oxabicyclo[4.1.0]heptan-2-ol, and 2, 3-pinanediol, which may contribute to its pesticidal properties [93]. The oil exhibited pesticide activity due to the fumigant and contact toxicities of their major components. Monoterpenoids found in oils can cause insect mortality by inhibiting the activity of the acetylcholinesterase enzyme [94], possibly activating octopaminergic receptors [95]. The essential oil extracted from the aromatic plants exhibited acetylcholinesterase enzyme inhibition at a high dose of 10^{-3} M. It can also affect the octopamine receptors of pests associated with respiratory movements and larval molting [95]. Aqueous formulation (1.5 %) of clove oil (*Syzygium aromaticum* (L.) Merr. & L.M.Perry) resulted in 98.54 % acaricidal properties [67]. Jatropha (*Jatropha curcas* L.) oil showed LC_{50}: 12.42 ppm [58] while nishinda leaf extract(*Vitex negundo* L.) had comparatively higher acaricidal potency (LC_{50}: 4.08 mg/mL) [57]. However, swamp shield-fern (*Cyclosorus interruptus* (Willd.) H.Itô) [69], gliricidia (*Gliricidia maculate* (Kunth) Steud.) [70], mugwort (*Artemisia vulgaris* L.) [68], floss flower (*Ageratum houstonianum* Mill.) [55], Spanish needle (*Bidens pilosa* L.) [55], horsetail (*Casuarina equisetifolia* L.) [55] showed comparatively lower acaricidal potency in laboratory studies.

3.1.3. Acaricidal activity of plant extracts in large scale field study

The acaricidal activity of the plant extracts is found to decrease in large-scale field settings compared to the laboratory studies (Table 1). However, the aqueous extract of *X. strumarium* has good acaricidal activity in both laboratory and field settings [59]. It reduces the TRSM population by 90.2 % within 14 days [59]. A comparable acaricidal activity (86.4 %) has also been observed in *A. calamus* in the same treatment period [59]. Several studies have reported that the aqueous extracts of *C. infortunatum* decrease the TRSM population by 81.63–100 % in agricultural settings [59,61,62]. In tea, azadirachtin at a dosage of 50,000 ppm is effective for controlling TRSM in field settings, even though the bioactivity may vary according to the insect [80]. These active chemicals have broad-spectrum bioefficacy against many pests. Approximately 25 kg of neem seed is needed to spray per hectare (ha) of tea plantation fields. The spray solution at 5 % concentration effectively repels the insect pests [96]. Extracts of sky flower *(D. erecta)* leaves and succulent stems have resulted in comparatively better efficacy against TRSM than azadirachtin (1 %) [41]. Moreover, it shows better efficacy than commercial synthetic pesticides such as propargite 57 % EC in field applications [41].

Extracts from other plants including *Datura metel* L., *L. camara, Swietenia mahagoni* (L.) Jacq*., A. marmelos, Linostoma decundrum* (Roxb.) Steud., *Phlogacanthus tubiflorus* Nees, *Sapindus mukorossi* Gaertn., *Phlogacanthus thyrsiformis* (Roxb. ex Hardw.) Mabb., *Nyctanthes arbor-tristis* L. also have acaricidal potency >60 % in the field conditions. Chebulic myrobalan (*Terminalia chebula* Retz.) has resulted in better acaricidal potency in field settings and caused an 89.2–100 % reduction in the TRSM population within seven days [39]. However, *Dicranopteris linearis,* (Burm.f.) Underw and *P. aquilinum* have been found to exert lower efficacy in large-scale field

Table 2
Some commercial botanical pesticides that are used in TRSM management.

Commercial name	Botanicals	Mode of action
Bio-Cawach	*Pongamia pinnata* extract containing Karanjin as the active ingredient.	• Mortality of pests results from the choking of the nervous system
Karanza	Neem *(Azadirachta indica)* and Karanj *(Pongamia pinnata) extract*	• Excellent commercial controlling agent against TRSM by contact poisoning
Miticon	Extracts of various herbs (alkaloids) and salt of fatty acids	• It exhibits pesticidal activity by contact as well as by stomach poisoning
Neemakar	Neem, Karanja, and Tulsi extracts	• It hampers the growth stages by acting as an antifeedant, repellent, and anti-ovipositor resulting in overall growth inhibition
Rescue	*Vitex negundo* + *Clerodendron infortunatum*	• It kills mites by direct contact and disturbs the life cycle by anti-oviposition & feeding deterrence.
Torpedo	*Sophora alopecuroides* + *Stemona sessilifolia*	• Torpedo can quickly and effectively eliminate susceptible pests by contact as well as by stomach poisoning. • This formulation disturbs the life cycle of TRSM and thus gives prolonged control.

Table 3

Application of microorganisms as biopesticides to control TRSM.

Sl. no	Microbial species	Laboratory study					Field study			Reference
		Spore Concentration in the aqueous suspension	Mortality			Treatment period	Dosage	Reduction of mite population	Treatment period	
			Egg	Nymph	Adult					
Fungi										
1.	*Purpureocillium lilacinum* (Hypocreales: Ophiocordycipitaceae)	-	-	-	57–87 %	7 days	–	–	–	[40]
2.	*Metarhizium robertsii* (Hypocreales: Clavicipitaceae)	5 %	-	-	68%–78 %	–	1200 mL/ 400 L/ha	65.93%–70.77 %	3 weeks	[7]
			90.4 %	92.2 %	90.0 %	2.2–2.6 days	–	–	–	[71]
		5 g/L	–	–	45.55–56.67 %	(24–72) hours	5 kg/ha	93.45 %	4 weeks	[27]
3.	*Beauveria bassiana* (Hypocreales: Cordycipitaceae)	5 g/L	–	–	37.78–52.22 %	(24–72) hours	5 kg/ha	90.48 %	4 weeks	[27]
4.	*Isaria fumosorosea* (Hypocreales: Cordycipitaceae)	5 g/L	–	–	52.08–68.72 %	(24–72) hours	5 kg/ha	96.37 %	4 weeks	[27]
5.	*Lecanicillium lecanii* (Hypocreales: Cordycipitaceae)	4 g/L	–	–	64.38–73.26 %	(24–72) hours	4 kg/ha	98.32 %	4 weeks	[27]
6.	*Aspergillus niger* (Eurotiales: Trichocomaceae)	1×10^8 conidia/mL	–	–	91.11 %	96 h	–	–	–	[72]
7.	*Aspergillus flavus* (Eurotiales: Trichocomaceae)	1×10^8 conidia/mL	–	–	62.22 %	96 h	–	–	–	[72]
8.	*Lecanicillium lecanii* + *Isaria fumosorosea* + *Hirsutella thompsonii*	1×10^8 spores/mL	–	95 %	85 %		–	–	–	[73]
Bacteria										
9.	*Pseudomonas putida* (Pseudomonadales: Pseudomonadaceae)	Extracellular filtrate and *P. putida* suspension	–	100 %	100 %	24 h	–	–	–	[74]
10.	*Streptomyces avermitilis* (Streptomycetales: Streptomycetaceae)	2 mL/L	–	–	58.46–71.11 %	24–72 h	2 L/ha	97.24 %	4 weeks	[27]
11.	*Pseudomonas fluorescens* (Pseudomonadales: Pseudomonadaceae)	5 g/L	–	–	56.67–64.46 %	24–72 h	5 kg/ha	95.99 %	4 weeks	[27]
		100 % bacterial suspension	–	–	100 %	24–72 h	–	–	–	[75]
		100 % extra cellular filtrate	–	–	100 %					
12.	Bacillus amyloliquefaciens (Bacillales: Bacillaceae)	1×10^9 CFU/mL	100 % (14 days)		100 %	96 h	–	–	–	[28]
13.	Bacillus subtilis (Bacillales: Bacillaceae)	1×10^9 CFU/mL	86.67 % (14 days)		93.33 %	96 h	–	–	–	[28]
14.	Bacillus velezensis (Bacillales: Bacillaceae)	1×10^9 CFU/mL	92.22 % (14 days)		100 %	72 h	–	–	–	[28]

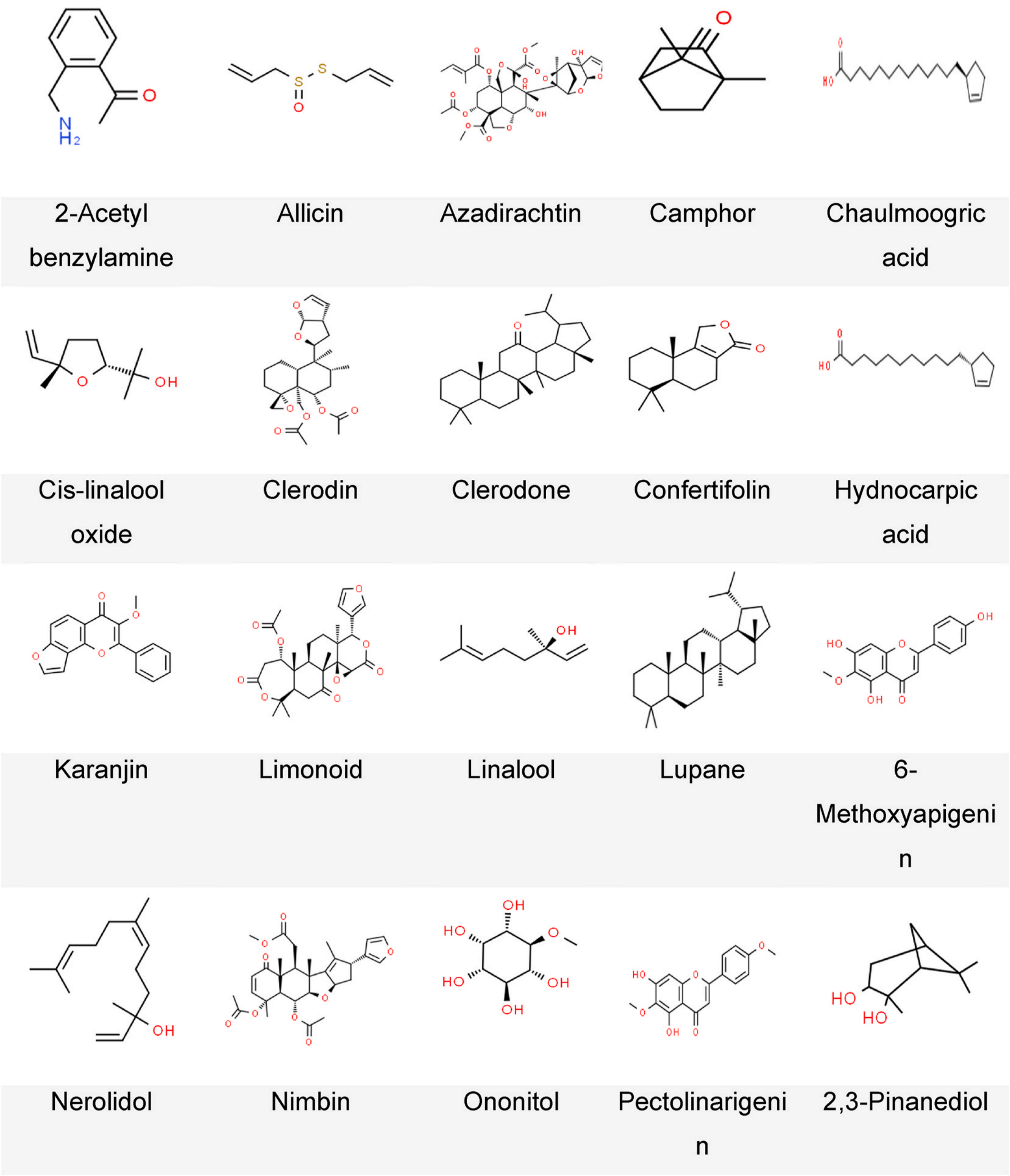

Fig. 2. The chemical structures of active substances found in plant extracts.

studies than in laboratory studies [69]. This review finds a clear disparity in pesticidal efficacy for laboratory tests versus field tests (Table 1). In most of the cases, the acaricidal potency was decreased in field studies which may be due to the interaction of AIs of plant extracts with environmental factors such as temperature, humidity [97], UV radiation [98], and rainfall or irrigation, degradation by soil microbes, volatility of active compounds, and uneven distributions. Moreover, behavioral adaptation of TRSM is another challenge in the case of biopesticide application, which only happens in field settings rather than laboratory [99]. These factors collectively contribute to the reduced acaricidal potency of plant extracts in field conditions, highlighting the challenges of translating laboratory efficacy to practical field applications. However, most of the information on botanicals is only available in laboratory settings [9,100]. This study emphasizes the necessity of conducting field studies on plant extracts to ascertain their effectiveness against TRSM.

3.1.4. Ovicidal action of pesticidal plant extracts

The active botanical ingredients effectively block the micropyle region of the TRSM egg, preventing gaseous exchange and ultimately leading to the death of the embryo within the egg [59].

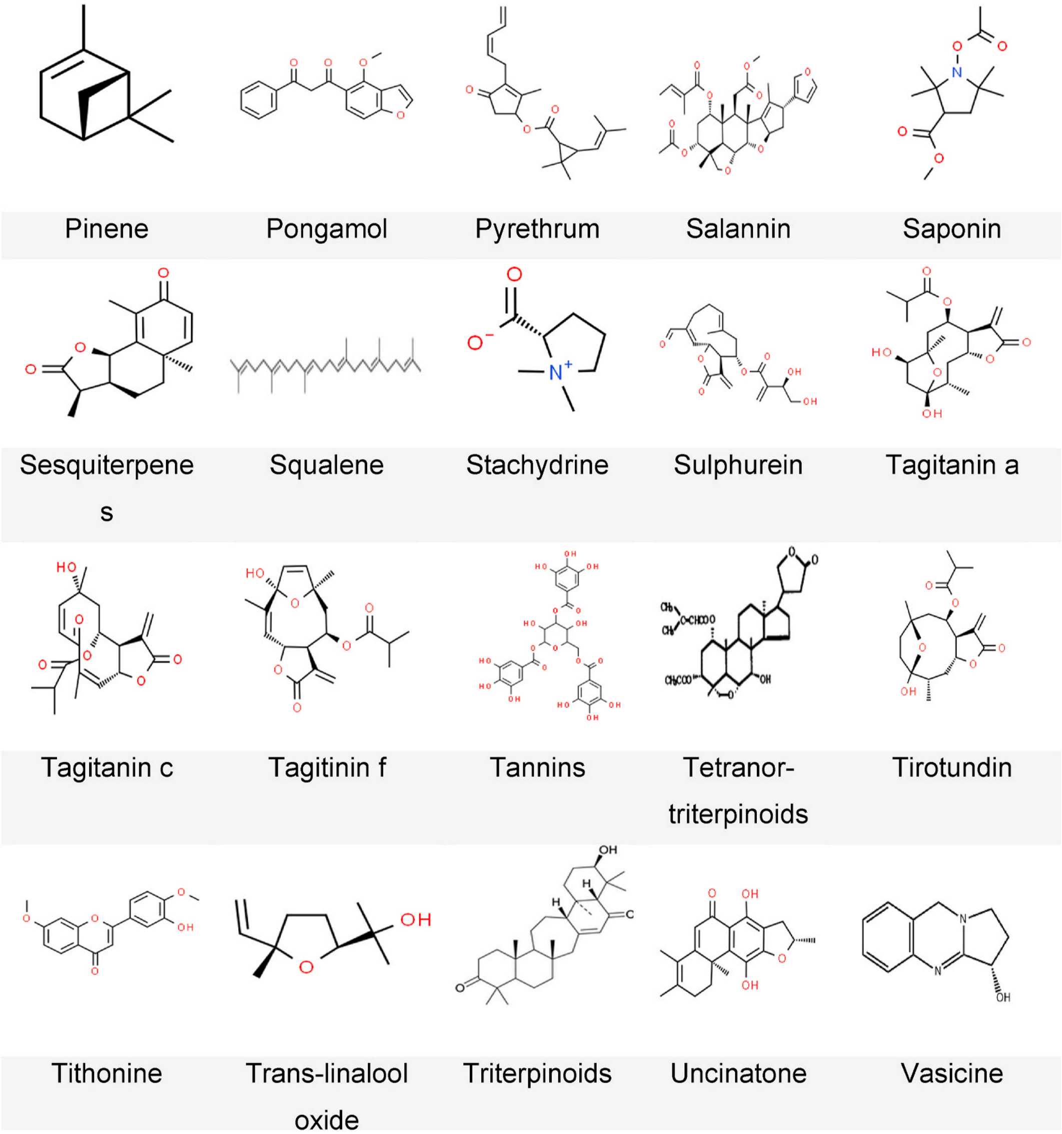

Fig. 2. (*continued*).

Table 1 represents the ovicidal activity of some plant extracts under laboratory conditions. Paradise-tree (*Simarouba glauca* DC.) seed oil has exhibited 90 % mortality of TRSM eggs. The ovicidal action may result from the fatty acids present in its seed oil when employed as contact sprays [101]. The highest potency was reported in the case of *H. pentandrus* seed oil which resulted in 100 % egg mortality at 5 mL/L concentrations. This oil may decrease the hatchability of insect eggs by interfering with embryonic developmental processes [63]. Moreover, common basil (*Ocimum basilicum* L.) [55], Fireweed (*Crassocephalum crepidioides* (Benth.) S.Moore) [55], and *H. pentandrus* [63] have maximum ovicidal potency (100 %) against TRSM.

The *P. juliflora* seed powder, when combined with neem kernel powder, acts as a botanical synergist and increases the ovicidal potency [23]. It may result in the highest egg mortality, up to 99 % [23]. Garlic aqueous extract at 5 % concentration caused more than 50 % mortality of TRSM eggs. Garlic oil is a promising biopesticide due to containing some organosulfur compounds, including allicin-derived sulfoxides, diallyl trisulfide, diallyl disulfide, diallyl sulfide, and diallyl methyl trisulfide [102–104]. Botanical extracts obtained from smartweed's (*Persicaria hydropiper* (L.) Delabre) leaves and succulent stems exhibited antifeedant and ovicidal activities when used at a concentration of 10 %. Confertifolin, which may possess insecticidal properties, was identified in the essential oil extracted from the smartweed leaves [105]. The petroleum ether and acetone fractions of *P. hydropiper* exhibited ovicidal activity [106]. The variations in ovicidal efficacy of plant extracts results from the incomplete blastokinesis and aberrant rupture of excess embryonic membranes in the embryo. Furthermore, the distinct pesticidal effectiveness may be associated with the uneven extract penetration through the egg chorion to different areas of the egg at different times during the sensitive phase [59].

Table 4
Application of predators as bio-control agents to control TRSM.

Sl No.	Common name	Scientific name	Predator status	Laboratory conditions				Field condition	Reference
				Average prey consumption/day				Population reduction	
				Egg	Larvae	Nymph	adult		
1.	**Phytoseiid mites**	*Amblyseius coccosocius* (Acari: phytoseiidae)	• Prey: predator (1:1)	–	–	–	–	100 % (7 days)	[138]
			• Prey: predator (1.5: 2)	–	–	–	–	100 % (8 days)	
			• Prey predator (6:1)	–	–	–	–	100 % (14 days)	
2.	**Ladybird**	*Stethorus gilvifrons* (Coleoptera: Coccinellidae)	• An adult female	205.0	92.2	81.8	52.4	–	[139]
3.	**Ladybird**	*Micraspis discolor* (Coleoptera: Coccinellidae)	• A larvae	–	–	–	280.30	–	[18]
4.	**Green lacewing**	*Chrysoperla carnea* (Neuroptera: Chrysopidae)	• A 3rd instar larvae	–	–	–	25–30	–	[65]
5.	**Predatory mite**	*Neoseiulus longispinosus* (Acari: Phytoseiidae)	• Deutonymph	6.1	17.2	11.2–12.0	4	–	[140]
			• Adult female	13.3	21.9	15.9–18.3	5.5	–	
6.	**Green lacewing**	*Mallada desjardinsi* (Neuroptera: Chrysopidae)	• Predator: prey (1:33)	–	–	–	99.6 %	–	[141]
			• Predator: prey (1:50)	–	–	–	98.8 %	–	[141]
			• Single larva	1254.1 (14 days)	1162.5 (14 days)	1055.3 (14 days)	934.7 (14 days)		[142]
8.	**Black coccinellid**	*Stethorus aptus* (Coleoptera: Coccinellidae)	• An adult predator	152–172	82–90	74–76	48–56	–	[143]
			• 3rd and 4th instar larvae	58.4–77.8	50–60	30.4–58.6	20–26	–	
9.	**Beetle**	*Oligota pygmaea* (Coleoptera: Staphylinidae)	• Third instar larvae	133.2	46.4	39.6	11.4	–	[144]
10.			• Adult male or female	31.4–49.4	20–30.8	16.4–23.8	5–8.4	–	

3.1.5. *Ovipositional deterrent and repellent activity of pesticidal plant extracts*

Neem kernel contains complex triterpenoid limonoid compounds including, azadirachtin, azadirachtin B, salannin, and nimbin [107], which are a major AIs with antifeedant, ovipositional deterrent, repellent, and growth disruption activities, as well as sterility effects [79,81,102,108–110]. Azadirachtin exhibits remarkable growth regulation, biocidal efficacy, and deterring effects on insect oviposition and feeding [111]. The brain inputs from an insect's chemical sensors such as the taste receptors in its mouthparts, tarsi, and oral cavity, are what determine an insect's feeding behavior [76]. The central nervous system receives information from these sensors as a "sensory code." By stimulating deterrent cells in these chemoreceptors and inhibiting the stimulation of eating in insects by activating "sugar" receptor cells, azadirachtin causes the manifestation of antifeedancy [112]. Aside from its antifeedant properties, injecting azadirachtin also induces physiological changes in the insect's midgut that reduce the effectiveness of its post-ingestion digestive system [113]. The physiological and hormonal systems are affected by this decrease in efficiency, referred to as "secondary" antifeedancy [114,115]. These issues include a restriction of food transit through the insect's midgut and a suppression of the generation of digestive enzymes [116]. An early investigation showed that azadirachtin had an insecticidal impact at 50–100 ppm [117]. Rapidly emerging secondary antifeedant and sterilant effects may suppress insect numbers and protect crops without harming nontarget or natural predator populations [117].

Azadirachtin interferes with the developmental processes of TRSM and causes a variety of sterility and molting abnormalities. It shares structural similarities and mimics the mite's growth hormones called "ecdysones," which regulate an insect's ability to undergo molting and developmental processes termed metamorphosis [118,119]. Thus, under exposure to azadirachtin, the metamorphosis of TRSM is hindered by preventing the production of ecdysteroid hormone and resulting in abnormal molting, growth inhibition, and increased mortality [120–122].

Furthermore, azadirachtin's cellular absorption prevents cell division and protein synthesis, leading to midgut cell necrosis and flaccid paralysis of muscles [114]. Products made from neem have a dose-dependent effect on female insects' ability to reproduce. By obstructing oogenesis and the production of ovarian ecdysteroids, azadirachtin hinders oviposition. Azadirachtin stops the sperm-producing meiotic process in males [123].

Additionally, a novel trypsin inhibitor isolated from *P. juliflora* seeds has shown significant activity against pest digestive enzymes, highlighting its potential use in pest control strategies [82]. Seed extracts from *S. mahagoni* are highly toxic to mite pests and utilized as

Table 5
Effects of biopesticides on yield and quality of tea and non-target organisms.

Biopesticides	Phytotoxic effect	Tainting	Organoleptic test				Residue	Effects on non-target organisms	Reference
			Organoleptic Score	Liquor	Color	Grade			
Plant based biopesticides									
A. indica + *P. juliflora*	No (grade 1)	No	–				No	–	[23]
A. indica	No (Grade 1)	No	–				No	Safer for beneficial insects such as predators	[10]
Azetar			–				–	Safe for *M. desjardinsi* and *O. pygmaea*	[25]
M. azedarach	No (Grade 1)	No	6.5–7.0	Good	Good		–	–	[26]
D. erecta	No (Grade 1)	No	6.5–7.0	Good	Good		–	–	[41]
X. strumarium	–	–	–				–	No adult Mortality of *S. gilvifrons*	[59]
A. calamus	–	–	–				–	No adult Mortality of *S. gilvifrons*	[59]
P. hydropiper	–	–	–				–	No adult Mortality of *S. gilvifrons*	[59]
P. hydripiper	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
X. strumarium	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
D. metel	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
L. camera	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
S. mahagoni	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
A. indica	–	No	32.20–33.80 (50-point scale)	Strong	Coppery	Above average	–	–	[60]
C. infortunatum	No (score 0–5%; grade 1)	No	6.5–7.0 (10-point scale)	Good	Good		–	–	[61]
M. paniculata	No	No	6.5–7.0 (10-point scale)	Excellent	Excellent	Excellent	–	No effect on *C. carnea*, *O. javanus*, and *S. gilvifrons*	[49]
C. tora	No	No	6.5–7.0 (10-point scale)	Excellent	Excellent	Excellent	–	No effect on *C. carnea*, *O. javanus*, and *S. gilvifrons*	[49]
A. oplentum	No	No	6.5–7.0 (10-point scale)	Excellent	Excellent	Excellent	–	No effect on *C. carnea*, *O. javanus*, and *S. gilvifrons*	[49]
T. diversifolia	No	No	6.5–7.0 (10-point scale)	Excellent	Excellent	Excellent	–	No effect on *C. carnea*, *O. javanus*, and *S. gilvifrons*	[49]
C. alata	No	No	6.5–7.0 (10-point scale)	Excellent	Excellent	Excellent	–	No effect on *C. carnea*, *O. javanus*, and *S. gilvifrons*	[49]
S. mukorossi	No (score 0–5%; grade 1)	–	6.0–7.0 (10-point scale)	Good	Good	Good	–	No effect on *S. aptus*	[66]
P. thyrsiformis	No (score 0–5%; grade 1)	–	6.0–7.0 (10-point scale)	Good	Good	Good	–	No effect on *S. aptus*	[66]
N. arbor-tristis	No (score 0–5%; grade 1)	–	6.0–7.0 (10-point scale)	Good	Good	Good	–	No effect on *S. aptus*	[66]
D. linearis	No	–					–	–	[69]
P. aquilinum	No						–	–	[69]
Microbial biopesticides									
M. robertsii	No		Acceptable				–	–	[7]
B. bassiana	–	–	–				–	No effect on *S. gilviforns* and *Oxyopes* spp.	[27]
I. fumosorosea	–	–	–				–	No effect on *S. gilviforns* and *Oxyopes* spp.	[27]

(*continued on next page*)

Table 5 (*continued*)

Biopesticides	Phytotoxic effect	Tainting	Organoleptic test				Residue	Effects on non-target organisms	Reference
			Organoleptic Score	Liquor	Color	Grade			
L. lecanii	–	–	–				–	No effect on *S. gilviforns* and *Oxyopes* spp.	[27]
P. putida	–	–	–				–	No effect on *S. gilviforns* and *Oxyopes* spp.	[27]
P. fluorescens	–	–	–				–	No effect on *S. gilviforns* and *Oxyopes* spp.	[27]

a botanical pesticide in tea plantations to control TRSM effectively [86]. Pesticidal potency may exerted due to some primary phytoconstituents, including tannins, saponins, alkaloids, and terpenoids [124]. Additionally, this extract contains a significant amount of bis(2-ethylhexyl) phthalate, which possesses repellent and insecticidal properties [125]. The *Duranta erecta* L. extract contains steroids, triterpenes, iridoids, diterpenoids, flavonoids, triterpene saponins, and saponins, which can occur the olfactory, gustatory, or contact sensitivities of TRSM adults to *D. erecta* extract may causes ovipositional deterrent, antifeeding properties in TRSM [41].

Tree marigold (*Tithonia diversifolia* (Hemsl.) A. Gray) leaf extract may cause 82 % adult TRSM mortality by exerting cytotoxicity [49]. The pesticidal potency may be attributed to the presence of sesquiterpene lactones. The leaf extracts contain some bioactive compounds, including 6-methoxyapigenin, tagitinins (A, B, C, and F), tirotundin, tithonine, and sulphurein and 2-hydroxytirotundin which are capable of deterring insect feeding [126,127]. In a laboratory study, chloroform extracts of *P. hydropiper* highly effective in killing TRSM and acting as antifeedants [128]. Extract of sickle senna (*Senna tora* (L.) Roxb) and ringworm cassia (*Senna alata* (L.) Roxb.) at 10 g/L resulted in 52 % adult TRSM mortality (Table 1). Ononitol monohydrate isolated from the ethyl acetate extract of this plant was reported to show significant antifeedant and larvicidal activities [129]. The chemical structures of important active substances present in the studied plant extracts are shown in Fig. 2.

3.1.6. *Marketed botanical pesticides*

Most botanicals demonstrated effective contact and fumigant toxicity against insects and mites. Several commercial biopesticides are already being used to control TRSM in fields, formulated based on plant extracts with different modes of action (Table 2).

The field test revealed that all the biopesticides had acaricidal properties that considerably decreased TRSM infestations. Miticon reduced the number of mites by 81.34 %, whereas Rescue reduced them by 81.01 %. The Bio-Cawach treated plot showed the lowest decrease in population density (74.07 %) of TRSM [60]. The Torpedo is the mixture of *Sophora alopecuroides* L. *and Stemona sessilifolia* (Miq.) extracts. It is a very effective biocontrol agent against TRSM by contact and stomach poisoning.

3.2. *Microbial biopesticides to control TRSM*

Entomopathogenic microorganisms (bacteria, fungi, viruses, or other protozoan groups) are the primary source of microbial pesticides because of their specificity in killing pests. These contain a microorganism as the active ingredient. Although the individual active ingredients in microbial pesticides are rather pest-specific, the pesticide is effective against various pests. The use of entomopathogenic fungus is becoming a very effective method to control TRSM in tea fields. They are unique in their mode of action and generally infect their hosts through the external cuticle. Microbial pesticides must be monitored regularly to prevent them from developing the capacity to cause damage to nontarget animals [51]. More than 40 fungal and bacterial species and 82 viral species are effective against tea insects and mite pests [130], whereas about 8 species of fungi and 3 species of bacteria are found to be effective against TRSM (Table 3).

3.2.1. *Bacterial pesticides*

In this current study, six species of bacteria such as *Pseudomonas putida* Trevisan*, Streptomyces avermitilis* Kim and Goodfellow, *Pseudomonas fluorescens* Migula*, Bacillus velezensis* Ruiz-Garcia, *Bacillus amyloliquifaciens* Priest, and *Bacillus subtilis* (Ehrenberg) Cohn were found to be entomopathogenic against TRSM (Table 3). Laboratory studies showed that *P. fluorescens* killed 100 % of the TRSM population after 72 h of exposure [75]. Testing *P. putida* suspension and extracellular filtrate on TRSM led to reduced mobility and cessation of feeding within 24 h, with 100 % death of nymphs and adults. Furthermore, after 8 days of treatment, the eggs still failed to hatch [74]. Application of *S. avermitilis* on adult TRSM resulted in significant mortality, ranging from 58.46 to 71.11 % [27]. Moreover, some pesticidal secondary metabolites released from the Bacillus species result in the mortality of TRSM. A recent study found some insecticidal metabolites, namely Brevianamide A, Heptadecanoic acid, Milbemycins D, Sterigmatocystin, Thiolutin, and Versimide, in the three studied *Bacillus* spp. including, *B. velezensis, B. amyloliquifaciens, and B. subtilis.* In laboratory settings, *B. velezensis* showed better efficacy compared to others when the concentration and treatment period were similar, possibly due to the secretion of Zwittermicin [1].

3.2.2. Fungal pesticides

In China, India, and Sri Lanka, experiments combining entomopathogenic fungus with synthetic pyrethroids or organophosphate substances yielded positive results [40]. Fungi use cuticle-dissolving enzymes like chitinase and protease to kill insects. *Lecanicillium lecanii* (Zimm.) Zare & W. Gams*, Isaria fumosorosea* Wize*,* and *Hirsutella thompsonii* (Fisher) formulations at 106, 107, and 108 spores/mL were tested in the lab against TRSM. In addition, when 3500 g of formulation/ha was administered under field conditions, nymphs and adults experienced 95 % and 85 % mortality, respectively, and mites were notably decreased [73]. *Metarhizium robertsii* (Metchnikoff) Sorokin has been reported to be detrimental to different stages of TRSM in a lab setting. Mites exposed to varying concentrations of fungal spores died at a rate of 60–90 % throughout all life stages in about 2–3 days [71]. Protease has a crucial function in the first invasion step during the penetration of the fungus *M. robertsii*. Moreover, *Beauveria bassiana* (Balsamo) Vuillemin and *M. robertsii* secrete several chitinase isozymes from their extracellular enzyme factories. Most insect deaths may be attributed to two proteins: beauverin in *B. bassiana* and destruxin in *M. robertsii.*

After 7 days of the administration, *Purpureocillium lilacinum* (Thom) Luangsa-ard et al. had a 57–87 % mortality rate of TRSM [40]. Various concentrations were used to compare the efficacy of *Aspergillus niger* Tiegh. and *Aspergillus flavus* Link against the TRSM. The pathogenicity of *A. niger* was more evident, causing 91.11 % of death after 96 h of treatment [72]. Researchers are trying to find entomopathogenic fungus species against TRSM. A previous study isolated a fungus species from the tea mite body, and the pathogenicity was evaluated against the mite, which resulted in 65 % mortality of TRSM [22]. This research suggests that fungus and bacteria are more effective at controlling tea TRSM than synthetic pesticides and may be utilized in organic tea production.

3.2.3. Mechanism of pesticidal activity exerted by bacteria and fungi against TRSM

A class of biopesticides known as microbial pesticides targets a particular issue by using naturally occurring bacteria, viruses, fungi, or protozoans [131]. In certain instances, the metabolites of these organisms may be where the pesticidal action initially manifests. By releasing either salicylic acid or components of the cell wall, certain bacteria and fungi can trigger defense reactions in plants. The action of various microbial pesticides depends on the type of microorganisms used [132,133]. Chitin (1, 4 – β – linked polymer of N – acetyl – β – D – glucosamine (GlcNAc)), the second most abundant biopolymer, is a major component of the exoskeleton and gut linings of insects [75]. Breakdown of the chitin layer of an insect by any process such as using the chitinase enzyme, might be a potential technique to mitigate the target pest. Chitinolytic enzymes hydrolyze the chitin of insects and retard growth and development. Spraying chitinase enzyme-carrying bacteria, fungi, and viruses on the surface of TRSM is a potential way to mitigate the pest as they degrade chitin into its monomeric or oligomeric components, either penetrating gut regions or disrupting the cuticle region made of chitin [75,134]. The breakdown of chitin causes abnormalities in feeding and molting.

Chitinases have a higher potential for IPM than other hydrolytic enzymes like glucanases or proteases since they are effective at breaking down chitin yet pose no threat to non-chitinous organisms like plants and vertebrates [135]. They can be classified into two categories based on their mode of action: endo-chitinases and exo-chitinases. Chitin chains are randomly cleaved by endo-chitinases at internal sites, producing soluble low-molecular-mass multimers of GlcNAc in the form of chitotetraose, chitotriose, and diacetylchitobiose. The removal of GlcNAc monomers or dimers from the non-reducing end of the chitin chain or the oligomeric products of endo-chitinases is facilitated by exo-chitinases [136]. In the case of entomopathogenic fungi such as *Metarhizium, Beauveria,* and *Purpureocillium*, chitinases directly attack the mite pests by penetrating the cuticle [137].

3.3. Uses of predators as biocontrol agents to control TRSM

Biological control of pests using predators is one of the oldest and most widely used techniques to control pests under economic injury levels [39]. Over 200 types of predatory arthropods have been documented in the tea ecology. Among them, 80 species of predators, including coccinellid beetles, phytoseiid mites, and lacewings, are dominant [39]. Table 4 represents some potential predators effective against TRSM.

Over seventy species of spider mites were identified as predators in tea ecology; among them, *Amblyseius coccosocius* (Ghai and Menon) and *Neoseiulus longispinosus* (Evans) were effective against TRSM. A field study reported that *A. coccosocius* decreased the TRSM population by 100 % within 7 days [138]. The *N. longispinosus* could also reduce the population of TRSM through rapid multiplication, and a predator-prey ratio of 1:25 to 1:33 can be considered optimal for field release [145]. On average, a predator consumed 1.62 adult female prey for every egg it laid [146]. Temperature is a factor that influences prey consumption, and the rate of predation significantly decreases at more than 25 °C. *N. longispinosus* preyed on all phases of the TRSM's life cycle, preferring larvae and nymphs [145]. It may be successfully exploited as a biocontrol candidate for TRSM by mass rearing and field release [145].

Micraspis discolor (Fabricius) is a major coccinellid predator in conventionally managed tea plantations in North Bengal, India [18]. The TRSM populations and their predator, *M. discolor*, exhibited comparable abundance patterns and reached their highest points from January to March. Researchers found that *M. discolor* grubs, while in the larval stage, ate an average of 280.30 red spider mites per day [18].

Stethorus gilvifrons (Mulsant) is another coccinellid predator of the TRSM [139]. The incidence of this predator depends on several environmental factors. Low temperatures, high humidity, and heavy precipitation adversely affected the *S. gilvifrons* populations. The population of *Stethorus aptus* (Kapur) showed a positive correlation with its prey TRSM and relative humidity [143]. The predatory efficiency of *S. gilvifrons* increased during the growth of larval instars [139]. In contrast, The adult *S. aptus* was more effective in preying on the TRSM than their larvae [143].

Green lacewing (*Mallada desjardinsi* Navas) larvae exhibited greater consumption of TRSM nymphs at 35 °C, while their consumption was minimal at 15 °C [142]. The tested neem-based pesticide, Azter and Neem Kernel Aqueous Extract (NKAE), had no significant impact on TRSM infestation [142]. Another species of green lacewing, *Chrysoperla carnea* Stephens, is also efficient in controlling TRSM [65]. A third instar larva of *C. carnea* consumes 25-30 adult TRSM per day, a rate comparable to that of *S. aptus.* However, *Oligota pygmaea* Solier was very efficient in consuming TRSM eggs (n = 132.2/day) at this stage [144]. Under laboratory conditions, the results show that the ovicidal activity is comparatively higher in *S. gilvifrons, S. aptus, and O. pygmaea* than the other studied predators.

3.3.1. *Volatile info chemicals emitted by TRSM-infested tea leaves invite specific predators*

Plants usually produce a variety of volatile substances in reaction to pest infestations, which in turn attract particular predators and parasitoids of pests [147]. A gas chromatographic study revealed that alpha-farnesene, beta-ocimene, and linalool are the information chemicals released from the TRSM-infested tea leaves. These volatiles attract the predator *N. longispinosus* to the infested tea leaves with more prey TRSM. There was a noticeable difference in attractiveness when comparing regular tea leaves to those mechanically damaged or previously infected [148]. Several factors, including plant species [149], spider mite species [150], and the density of spider mites [148] are related to the volatiles synthesized by plants during mite infestation. Predatory action on prey is a complex process, and the degree of attraction is regulated by several factors, such as the predator's starvation period, the severity of prior infestations, and the volatiles released by the prey infested leaves. A tri-trophic interaction among predators, prey, and plants is developed [148]. *O. pygmaea* and *S. gilvifrons* are the most common predators in TRSM-infested areas. TRSM-infested plants emit several volatile info chemicals β-ocimene, α-farnasene, methyl salicylate, and *cis*-3 hexenyl acetate. A study on the behavioral responses of predators showed benzaldehyde, methyl salicylate, β-ocimene, α-farnasene evoked the maximum response in *O. pygmaea,* whereas *S. gilvifrons* elicited a higher response to methyl salicylate and benzaldehyde [151].

3.4. *Phytotoxic effects of biopesticides*

Table 5 represents the phytotoxic effects of the studied biopesticides on tea plants under field conditions. The phytotoxic symptoms are assessed based on changes in the appearance of the tea leaves due to the application of biopesticides [61]. Among them, leaf tip injury, leaf surface injury, leaf wilting, necrosis, vein clearing, epinasty, and hyponasty levels are measured and graded from 1 to 10 at 10 % intervals [23]. Notably, NKAE with botanical synergist (*P. juliflora*) was found to be non-phytotoxic (grade 1) to tea at both 5 % and 10 % concentrations [23]. Another field study on NKAE also reported non-phytotoxic effects ranging from 1 to 10 % (grade 1) [10]. Extracts of *M. azedarach*, *D. erecta*, *C. viscosum, N. arbor-tristis, P. thyrsiformis*, *S. mukorossi, D. linearis,* and *P. aquilinum* had no phytotoxic effects on the tea leaves up to 60–63 days after spraying [26,41,69,61,66]. The aqueous extracts of *M. paniculata, C. tora, A. oplentum*, *T. diversifolia, C. alata* were also safe for tea leaves and had no phytotoxic effects [49]. Furthermore, 5 % aqueous suspension of *M. anisopliae* has been found to decrease the TRSM population significantly without causing any phytotoxic symptoms in tea plant [7].

3.5. *Effects of biopesticides on organoleptic properties of made tea*

The tainting of food is a major concern in the food industry, caused by foreign chemicals from an external source. The presence of tainting compounds can greatly affect the quality and consumer acceptance of products, even at low concentrations [152]. Identification of thus compounds responsible for food tainting is a very critical approach [152]. In the case of tea, the taint is commonly assessed through sensory analysis by professional tea tasters [10,23]. It is generally recognized as a bad odor resulting from the release of volatile compounds [152]. Taint formation from the use of synthetic pesticides is a very common problem in tea industries [9]. However, the use of biopesticides can reduce this critical issue in made tea (Table 5). The NKAE and botanical synergist had no taint in the made tea samples processed in the CTC (Crush, Tear, and Curl) unit, which were harvested 1, 3, 5, 7, 10, and 14 days after the application [10,23].

Tea samples treated with *M. azedarach* seed extracts, as well as *C. infortunatum* and *D. erecta* leaf extracts, showed no taint and an organoleptic score of 6.5–7.0, indicating good liquor, strength, and colour quality [26,41,61]. Aqueous extracts from *P. hydripiper, X. strumarium, D. metel, L. camera, S. mahagoni,* and *A. indica* showed no impact on the sensory characteristics of made tea. Organoleptic evaluations indicated that the leaf infusions of made teas as coppery, with a strong liquor strength, scoring between 32.20 and 33.80, which falls above average (AA) on a 50-point scale [153]. Likewise, after the application of pesticidal plant extracts *N. arbor-tristis, P. thyrsiformis, S. mukorossi, M. paniculata, C. tora, A. oplentum*, *T. diversifolia, C. alata*, tea shoots were plucked on days 1, 3, 5, 7, 10, and 14, and manufactured samples were tested by professional tea tasters. The made tea exhibited no undesirable characteristics and achieved a score of 6.0–7.0 in the organoleptic tests, which represented excellent color, liquor, quality, and potency [49,66].

3.6. *Pesticide residues and effects on non-target organisms*

The presence of pesticide residues in processed tea due to the use of synthetic pesticides has emerged as a significant concern to both tea consumers and producers [11,154]. Several studies reported the incidence of pesticide residues including, bifenthrin [155, 156], chlorpyrifos [157], dichlorovas [156], difenaconazole [156], emamectin [156], glyphosate [156], Imadachloroprid [156], isocarbophos [157], triazophos [157] in the made tea, which may lead to the several carcinogenic and noncarcinogenic diseases under consumption [11,154]. However, the evaluation of the efficacy of any chemical will be complete only when it is tested against the natural enemies of the pests. Table 5 shows the effects of some biopesticides on the non-target organism. NKAE was found as safer for beneficial insects such *O. pygmaea*, and it does not leave any undesirable residues on black tea [10]. Other studies reported that

A. indica extracts had no impacts on the *C. carnea, O. javanus*, and *S. gilvifrons* [49] *and Oxyopes* spp [153]. The neem product such as azter had no significant effect on the eggs, larvae, and adults of *M. desjardinsi* under direct spraying [25]. The lowest toxicity may be due to the presence of a waterproof chorion and long stalk in the egg. Moreover, it didn't have any effect on the life stages of *O. pygmaea* [25]. However, fenpropathrin, a chemical pesticide used to control TRSM, had adverse effects on *O. pygmaea* [10]. Even at a high concentration (10 %), *P. hydripiper, X. strumarium, D. metel, L. camera, S. mahagoni, and A. indica* extracts were safe against *S. gilvifrons* and *Oxyopes* spp [153]. Aqueous extracts of *N. arbor-tristis, P. thyrsiformis, and S. mukorossi* caused no mortality or decrease in the predation efficacy of the adults and fourth instar larvae of *Stethorus aptus* Kapur, a natural predator of *O. coffeae* [66]. The use of *M. paniculata, C. tora, A. oplentum, T. diversifolia, C. alata* extracts as biopesticides did not have any adverse effect on the non-target beneficial organisms such as, *C. carnea, O. javanus*, and *S. gilvifrons* [49]. Among the microbial pesticides tested, application of *B. bassiana, I. fumosorosea, L. lecanii, P. putida*, and *P. fluorescens* did not affect the nontarget organisms such as *S. gilviforns* and *Oxyopes* spp [27].

4. Nanotechnology in biopesticide

4.1. Employment of nanotechnology to increase the effectiveness of biopesticides

Although biopesticides offer many advantages, they also have some shortcomings that limit their usage in tea plantation fields. Among the shortcomings, high dosages of biopesticides are needed for effective control in field conditions. Sometimes, it has a very short shelf life due to its high biodegradability rate. Furthermore, environmental conditions like as desiccation, heat, light, and ultraviolet radiation can limit the action of microbial pesticides [36]. Technological advancements such as nanotechnology are expected to overcome the constraints of the conventional methods of biopesticide applications, offering innovative and sustainable solutions in agriculture. Nano biopesticides refer to pesticides that consist of chemical complexes derived from biological sources with nanoparticles. Nano biopesticides are formulated with very small particles of active ingredients or other small-engineered structures at the nanometer scale (1–100 nm), which carry the biologically derived active ingredients to prevent, destroy, repel, or mitigate pests [158]. These nanoparticles are incorporated to enhance the delivery efficiency and effectiveness of the pesticides. The large surface areas of nanocarrier materials increase their ability to carry pesticides, which in turn increases their dispersal properties and tendency to cling or adsorb to certain insect species or groups [158]. Due to enhanced dispersion stability, the nanoscale formulations provide better distribution of the products within the target areas. To meet the criteria for qualification, nano biopesticides should possess certain properties, including increased solubility of active ingredients with low solubility, controlled release of active ingredients targeted towards specific sites, and resistance to premature degradation [159].

These developments aim to mitigate the negative impacts of pesticides on the environment by employing slow- or controlled-release techniques, wherein active ingredients are encapsulated at the nanoscale. The sustained and controlled release of the active ingredients over time provides substantial advantages in field applications, enhancing the precision and efficacy of these agricultural products [160]. This approach addresses the drawbacks of conventional methods of pesticide applications and reduces the potential harms associated with it [161]. Additionally, by tailoring the synthesis of nano biopesticides based on understanding the life cycle and behavior of the targeted pathogens or pests, their specificity and impact can be heightened.

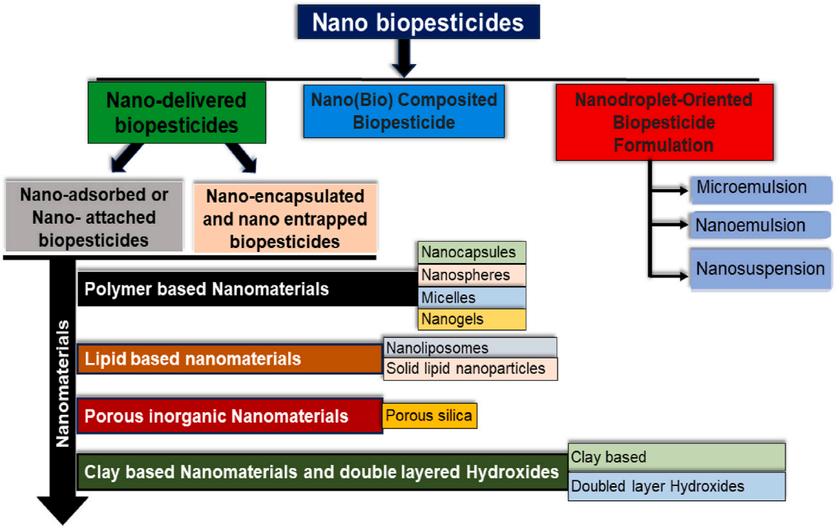

Fig. 3. Methods of developing nano biopesticides using nanotechnology.

4.2. Methods of development using nanotechnology

Biocompatible and more efficient biopesticides can be generated by encapsulating biomolecules extracted from plants, fungi, and bacteria with sustained action or through the various biomaterials synthesized by biogenic processes [162]. Several natural substances are used to formulate nano biopesticides and can be categorized into two broad groups: (i) nanoparticle pesticides and (ii) nanocarrier systems to achieve the effective delivery of active ingredients to the target sites of pests [163]. Fig. 3 represents the methods of developing nano biopesticides.

4.2.1. Nano-delivered biopesticides

Nano-delivered biopesticides are commonly used pesticides where the nanomaterials are used as carrier material for specific delivery of active ingredients. These nanomaterials can be classified as polymer-based (nanospheres, nanocapsules, nanogels, and micelles), lipid-based (nanoliposomes, solid lipid nanoparticles), porous inorganic (porous silica) and clay-based nanomaterials and double layered hydroxides. Nanoparticles are formed to carry a particular biomolecule to an organ, tissue, or even a cell, and when combined with a nanocarrier, they can precisely deliver the contents inside an insect or plant cell [164,165]. The nanoparticles enter the plant cells and can significantly alter these systems by opening up new pores through ion channels or attaching to a carrier protein [165]. The active substances such as botanical extracts, enzymes, essential oils, microbial extracts, and microbes are loaded into the carrier materials through adsorption or attachment via ligands at the outer surface or encapsulating them into the carrier materials. Nano-delivered biopesticides can be developed through nano adsorption or nano attachment of active substances to the outer or inner surface of nanocarrier materials via van der Waals forces along with other weak forces of attraction such as hydrophobic- and H-bonding interactions or by cross-linking. Nanoencapsulation or entrapment of AIs into polymer-based nanomaterials, lipid-based nanomaterials, porous inorganic nanomaterials, and clay-based nanomaterials and double-layered hydroxides are very effective ways to pesticide delivery to the target pests. Several advantages are achieved, including controlled release of biopesticides and lower chances of degradation of AIs by enzymatic actions [158].

4.2.2. Nano (bio) composited biopesticides

Nano-composited biopesticides are multiphase solid compounds in a complex matrix with at least one phase composed of nanomaterials. These are categorized into three groups: (i) polymer matrix nanocomposites (PMNC), (ii) ceramic matrix nanocomposites (CMNC), and (iii) metal matrix nanocomposites (MMNC). Among them, the development of polymer matrix nanocomposites is well established, which includes two phase materials: dispersed phase (nanoparticles) and continuous phase (polymer matrix). These are mostly used for pesticide preparations and biopesticide formulations [158]. Biopolymers such as cellulose, gelatin, starch, and chitosan, are widely appreciated in developing bio-nanocomposites.

4.2.3. Nanodroplet-oriented biopesticide formulations

Developing nanodroplet-based pesticide formulations such as microemulsions or nanoemulsions, offers a promising and environmentally friendly alternative to traditional emulsions. These formulations eliminate the use of harmful organic solvents. Both microemulsion and nanoemulsion formulations are often considered translucent or transparent dispersions of active chemicals, whether in water or oil, that have been solubilized with additional components like surfactants. These two formulations are structurally identical since they include the same three key ingredients: water, surfactants, and oil. The droplet sizes generally range from 20 to 200 nm [158]. The nanoformulation significantly influences the properties of the active ingredients in nano biopesticides. Therefore, before their application, it is crucial to establish factors such as the shape, size range, surface properties, nature of the nanoparticles, the adjuvants utilized, and release characteristics over time under realistic conditions [159].

4.3. Development of botanical nano biopesticides

The effectiveness of botanical pesticides can be assessed by measuring the solubility of their active ingredients (AIs). The solubility depends on the lipophilicity and dissociation constant, which are determined by the chemical structures. Some are highly soluble in water, others dissolve in oil, and some are insoluble. The efficacy of botanical extracts on pests can be improved through encapsulation in nanostructured systems [166]. The nanoformulation of botanicals increases the stability and solubility of their AIs. Additionally, the use of oil-based nanoemulsions enhances the interfacial area between components, thereby facilitating the dispersion of oil across a broader surface area. This, in turn, enhances the potency of biopesticides [166].

Certain nanoformulated biopesticides that have improved effectiveness include essential oils coupled into various matrices, metal or metal oxide nanoparticles developed through green synthesis, and naturally occurring pesticide-effective organic or inorganic (poly) components [167]. Enzymes, primary and secondary metabolites, entire cells, and biomolecules are combined with nanostructure to create new bio-nanomaterials with pesticidal, pediculicidal, and larvicidal action [168]. Nano-synthesis techniques have been developed to produce carbon, metal, and metal oxide nanoparticles with various biological activities using microbial and botanical extracts for isolating, reducing, and stabilizing agents. Pesticidal plants and microorganisms can reduce metal ions (such as silver and gold) relatively moderately or fast under ambient conditions and start the biogenesis of nanoparticles. This type of bio-reduced nanoparticles can be used in biointensive integrated pest and disease management [168]. The allegedly "green fabrication" of nanoparticles and nanocomposites has been considered preferable to conventional chemical and physical techniques because it is frequently quick, affordable, and does not require highly toxic chemicals, high pressure, energy, or temperature [169].

Nanoparticles generated through biological processes have different actions and impacts on plants and insect pests than nanoparticles created through chemical processes. Nanoparticles have a large surface area, making it easy to circulate in an insect's system and swiftly bond with other substances [165]. A study comparing the larvicidal efficacy of *A. vulgaris*-derived AuNPs to that of the essential oil through its principal components (caryophyllene oxide, α-humulene, and β-caryophyllene) against 3rd and 4th instar larvae of the *Aedes aegypti* L. revealed that AuNPs were more effective in inflicting damage to the epithelial cells, midgut, and cortex after 24 h of exposure [170]. *D. linearis* synthesized AgNPs were studied to develop effective nanoformulated oviposition deterrents against dengue vectors [171]. *P. aquilinum* synthesized AgNPs were reported to show high mosquitocidal activity against *Plasmodium falciparum* Welch [172]. Synthesized silver nanoparticles *M. tinctoria* showed high mortality of third instar larvae of *Culex quinquefasciatus* Say [173]. *O. basilicum* AgNPs were reported to be a more effective and ecofriendly alternative for managing *Spodoptera litura* Fabricius [174]. According to studies, plant secondary metabolites in nanocarrier materials cause indigestion, disintegrate the water protection barrier, and cause insect mortality [175]. The insecticidal activity and shelf life were considerably enhanced by mixing a specific plant extract with nano-silica [176]. According to reports, the majority of terpene molecules have antifeedant properties. Alpha-pinene and linalool, two terpene chemicals, are combined with nano-silica to create a nanoformulation, which not only enhances efficacy (antifeedant action against *Achaea Janata (Linnaeus)* and *S. litura*) but also extends shelf life by over six months [176, 177].

Because they inherit some key characteristics such as permeability, crystallinity, stiffness, thermal stability, and biodegradability, which are more advantageous than commonly applied synthetic pesticides, nano biopesticides can be used directly or indirectly as vectors to combat tea pests. Due to their small dimensions, efficiency when sprayed in the field, improved droplet adhesion on the plant's surface, quick absorption by the target, and wettability, nano biopesticides offer competent and environmentally friendly benefits. Nano biopesticides enable the sustainable production of tea by decreasing the chemicals used, improving plant protection, and eliminating cashew gum nanoparticles incorporated with extracts from moringa (*Moringa oleifera* Lam.) seeds, demonstrating long-lasting effectiveness as a larvicide, even 55 days after preparation. Nano biopesticides prepared from cashew gum and moringa resulted in mortality up to 98 ± 3 % in third-instar larvae of *Stegomya aegypti* L [178]. *P. pinnata* leaf extract-coated zinc oxide nanoparticles (Pp-ZnO NPs) caused 100 % mortality of the pulse beetle, *Callosobruchus maculatus* Fabricius [179]. *Camara* nano suspension showed stronger antifeedant activity against *Crocidolomia pavonana* Fabricius [180]. The efficacy of nano formulations of the above-mentioned plant extracts against TRSM can be studied and compared to the direct application of the extracts.

Neem aqueous extract containing azadirachtin has excellent insecticidal properties against TRSM. However, herb-based pesticides have the drawback of having a short shelf life and degrading when exposed to sunshine. Additionally, active components of neem have non-specific toxicity. Nanocapsules, on the other hand, offer gradual, controlled, and cyclic construction. It permits controlled, prolonged release of the active substances at the action site, limiting harmful effects on nontargets. They also avoid the loss of volatile compounds, which improves phytochemical stability [181]. Azadirachtin was incorporated with carboxymethyl chitosan with ricinoleic acid (R-CM-chitosan) as a carrier, providing a better-controlled release of the pesticide [155]. Both organic [155] and inorganic [182] nanoparticles may contain active compounds from neem, primarily azadirachtin. Silver nanoparticles (NPs) can be produced by the biosynthesis of reducing phytochemicals found in neem leaves [183]. Such NPs with neem leaf extract caps can be effective biopesticide delivery systems for insecticidal action. Neem oil can also be added to silica-based NPs. When compared to the chemical pesticide imidacloprid, they showed no discernible difference in their insecticidal effectiveness [184]. In a different study, neem oil nanoemulsions made from the plant's seeds were created to slow the high rate of biopesticides based on neem's strong degradability. Controlling mosquito larvae was more effective with neem oil nanoemulsion containing the smallest droplet size than formulations with larger droplet sizes [185]. This nanoemulsion formulation also demonstrated strong UV stability [186]. A nanoemulsion composed of neem oil and non-ionic surfactant Tween 20 of 31.03 nm size was reported to be an effective larvicidal agent against *C. quinquefasciatus* [185]. In another study, neem seed oil was released utilizing alginate–glutaraldehyde as an encapsulating agent for pest management [187].

Insect pest and pathogen control using essential oils, their constituents, and semiochemicals (allelochemicals and pheromones) has emerged as a potential eco-friendly alternative. *H. pentandrus* seed oil, garlic oil, orange jasmine oil, and *S. glauca* seed oil showed significant egg mortality and adult mortality of TRSM. Since environmental factors such as oxygen, pH, mild temperatures, and light can rapidly degrade essential oils and plant extracts, they are biologically unstable [188]. Furthermore, there are still several limitations to the practical application of this molecule because of its volatile nature, poor water solubility, and limited chemical stability [189]. Therefore, it is necessary to develop methods that allow their use without affecting their biological and chemical characteristics. Currently, oil-in-water nano/microemulsions are thought to be effective methods for utilizing the bioactivity of essential oils and their constituents to combat insects and other infections. Chinaberry oil-loaded nanoemulsion showed improved acharicidal activity against the camel tick *Hyalomma dromedarii* Koch [190]. Clove Oil (*S. aromaticum*) nanoformulation showed effective larvicidal activity against *Culex pipiens* L. larvae [191]. Nanoemulsion of *V. negundo* essential oil was reported to be thermodynamically stable with larvicidal activity against dengue fever vector *A. aegypti* [192]. The larvicidal and pupicidal activity of Lantana essential oil-loaded nanoemulsion formulation were studied and showed effective mosquito control [193]. The protection provided by the hydrophobic environment created within the droplets can be combined with enhanced molecular dispersion in an aqueous environment by using nano/microemulsions. It facilitates the manipulation of bioactive substances and limits their degradation without compromising their biological efficacy [189]. Hence, by finding the active compounds of essential oils and plant extracts, their mode of action can be studied, and effective biopesticide products can be developed using nanotechnology to combat TRSM. Garlic oil significantly reduced the number of TRSM eggs and adults, showing a high LC_{50} value. In a study on the efficacy of a nanoemulsion of garlic essential oil primarily composed of sulfur compounds against the Confused Flour Beetle (*Tribolium confusum),* it was reported to have higher and more stable repellent activity, remarkable toxicity, and a lower RC_{50} value. The nanometric scale of the essential oil-based nanoformulation, which improves the bioactivity and bioavailability of the active components, can be responsible for the significant toxicity that it displayed [194]. In another study, polyethylene glycol (PEG) coated nanoparticles incorporated with garlic oil against adult *Tribolium castaneum* showed slow and persistent release of the active components from the nanoparticles with 80 % control efficacy compared to free garlic essential oil (11 % control efficacy) [195]. Therefore, the nanoformulation of garlic oil can be tested against TRSM for increased toxicity and mortality.

4.4. Development of microbial nano biopesticides

Nanotechnology can also improve the efficacy of microbial biopesticides against TRSM. The ability of bacteria to decrease metal ions through active absorption has encouraged using these organisms to produce antagonistic nanoparticles to control insects and other pests. Over the last two decades, several bacterial species, including *Bacillus* spp., *Corynebacterium* spp., *Pseudomonas* spp., and *Shewanella* spp., have been used to synthesize NPs utilizing different inorganic metals such as Ag, Al, Au, MnO, ZnO, and TiO_2 [168, 196]. Silver nanoparticles (AgNPs) have reportedly been extracted from *Bacillus* species with nematicidal, antibacterial, and pesticidal activities. The nanocomposites of the entomopathogenic bacterium with bioactives in various nano-formulations such as nanocapsules, nanosuspension, and nanoemulsion have been utilized as nano-pesticides [196]. Due to its target specificity, baculovirus-mediated prevention of insects is safe for the environment; however, its large-scale implementation in agriculture is relatively limited because of its low yield, restricted range of target organisms, and delayed killing rate [197]. At the field level, baculovirus can be effectively deployed through slow release nanoformulations that incorporate polymer or porous inorganic nanomaterials. The nanocarrier system's large surface area will help increase the formulation's affinity for the targeted insects.

Additionally, budded virions enclosed in nanomaterials can be utilized directly to control insects, eventually shortening the time needed to infect more insects [197]. The 2 % nanoencapsulated mixture of *A. flavus* and Phyto extract, *Cuscuta reflexa* showed greater larvicidal effect against 3rd instar larvae of *Anopheles stephensi* and *C. quinquefasciatus* and the bioefficacy of the nanoformulation increased with the increase of time [198]. The nanoemulsion formulation of *P. lilacinum* was reported to be effective in managing root-knot nematode (*Meloidogyne incognita* Kofoid & White) and showed better crop health benefits [199]. *I. fumosorosea*-based zero-valent iron (ZVI) nanoparticles showed high pathogenicity against second and third-instar nymphs and pupae of sweet potato whitefly *Bemisia tabaci* (Gennadius) [200]. Zinc oxide nanoparticles (ZONPs) synthesized from *A. niger* larvicidal activity against white grubs (*Holotrichia* spp.) [201]. Further study should be conducted to develop nanoformulations of microorganisms (e.g., *A. niger* and *P. putida*) that showed significant pesticidal activity against TRSM.

5. Strength and limitations

This study offers a comprehensive analysis by incorporating previously studied botanical extracts, entomopathogenic microorganisms, and predators, thoroughly comparing their effectiveness against TRSM. This study also includes the pathway of their actions. Additionally, this study highlights some potential active ingredients of plant extracts that may be responsible for TRSM mortality. However, very few studies were accomplished on the active ingredients examining their potency against TRSM. Again, nanotechnology is a very new concept for developing nano biopesticides. This study also describes the employment of nanotechnology to increase the effectiveness of biopesticides. However, we did not represent the studied plant and microorganism-based nano biopesticides on TRSM as a lack of original study. This study suggests that more research is needed to develop nano biopesticides to control TRSM effectively in the plantation fields.

6. Conclusion

The pest control system recently transitioned from scheduled, broad-spectrum insecticide applications to more systemic, integrated, and highly effective alternatives. Moreover, the main factors influencing modern pest management practices in commercial agriculture are ecological preservation, food safety, and resistance management. Authorities are considering regulating some pesticides and other agricultural goods, prompting the hunt for safe pest control alternatives. Several secondary chemicals produced by plants and bacteria have defensive properties. Their action targets are fairly diverse, and using these properties for efficient pest management is worthwhile. The findings suggest that essential oils may be a new generation of extremely physiologically active chemicals and alternatives to manufactured materials. *H. pentandra* and *S. glauca* seed oils reportedly showed 90–100 % TRSM egg mortality. The aqueous extracts of *C. viscosum, A. catharitica, P. pinnata, M. tinctoria*, and the neem-based pesticide Azter significantly reduced the adult TRSM population in the field. Moreover, some predators, including *M. discolor, S. gilvifrons* and entomopathogenic microorganisms, including *A. niger, P. putida, P. fluorescens* are very effective biocontrol agents against TRSM. Despite numerous reports of potent botanical compounds with pesticidal action, botanical pesticides currently make up only 8 % of the global pesticide market. The success of biopesticide commercialization can be attributed to raising awareness within the farming community of the negative impacts of chemical protectants. In this regard, the uses of nano biopesticides in tea cultivation have substantial scopes. Nanotechnology adds features to biopesticides, which make them more effective and efficient in controlling TRSM. Global commitment is needed to support these environmentally friendly alternatives, eliminate toxic compounds from our diet, and promote sustainable tea production. The study concludes by emphasizing the necessity for additional research to develop nano biopesticides for effective TRSM control in plantation fields.

In summary, this study offers a comprehensive overview of various pest control methods against TRSM, delving into their mechanisms and identifying potential active ingredients. However, it also highlights the limited research on active ingredients and the absence of empirical studies on nano biopesticides, underscoring the need for further investigation in these areas to enhance TRSM management strategies.

Data availability statement

Data will be made available on request.

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CRediT authorship contribution statement

Jahid Hasan Shourove: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Fariha Chowdhury Meem:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Razia Sultana Chowdhury:** Writing – review & editing, Visualization. **Shamima Akther Eti:** Writing – review & editing, Visualization. **Mitu Samaddar:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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