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Back to the origins: biopesticides as promising alternatives to conventional agrochemicals

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Abstract Presently, the world is using eco-friendly products to limit pollution in soil, air, water, and marine environments and to mitigate rapid climate change according to the sustainable development goals of the United Nations Development Programme. As a result, most countries attempt to produce environmentally friendly herbicides, fertilizers, and pesticides from plants, algae (e.g., *Cladophora glomerata, Laurencia pinnata*, *Plocamium cartilagineum, Polcamium* spp.) or animal manure. Plants, such as *Anethum sowa*, *Thymus vulgaris*, *Foeniculum vulgare*, *Syzygium aromaticum*, *Pinus sylvestris*, *Citrus* spp., *Piper* spp. and *Mentha spicata*, are ecofriendly sources of essential oils, containing safe components, which can resist harmful pests. This review evaluates the common plants and algae used for extracting biopesticides, geographical distribution, target pests, mode of action, and commercial viability.

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Introduction

The world's population is increasing tremendously and is expected to reach 8.5 billion by 2030. Conversely, food will decrease due to various reasons including harmful pests (Desa, 2011) and land for agriculture becoming less (Jhala et al., 2020). Annually, many crops are spoiled by an estimated 67,000 pests like fungi, weeds, bacteria, and insects (Agrios, 2005; Meena & Mishra, 2020). Using plants and algae for controlling pests is not new and is a traditional method (Choi et al., 2004). Biopesticides, originating from natural products (plant, algae, fungi) are eco-friendly, less toxic, and have less resistance build-up among insects and pathogens (Regnault-Roger et al., 2012). Biopesticides are effective because they have specific targets, and inhibit or kill harmful pests without negative effects on humans and beneficial organisms. Pests are a major factor in the declining yield of crops, which influence economies and feed populations (Sinha & Biswas, 2011).

Biopesticides are biodegradable and promote eco-friendly environments (Mazid et al., 2011). Safe plant and algae biopesticides are commercially available (Alam et al., 2002). In the United States of America, almost 200 biopesticides are used against harmful pests (Kumar & Singh, 2015), while in India 2.89% of the total market are biopesticides, which are increasingly used (Thakore, 2006). Biopesticides mainly derived from plants and algae have gained attention and publicity due to potentially healthier benefits in agriculture and for human health (Gupta & Dikshit, 2010). It possesses antifungal, antibacterial, antivirus, and insecticidal biopesticides (Akinbode & Ikotun, 2008; Hao et al., 2021; Harlapur et al., 2010; Yasmin et al., 2008).

Plant-based pesticides are commonly derived from herbs and plant-based pesticides are known as herbal pesticides (Pal et al., 2013). Almost 6000 plant species are used as insecticides (Dimetry et al., 1993). Different forms of algae are potential biopesticides. Microalgae are a microscopic group of algae that have bioactive compounds, which are effective against harmful organisms (Costa et al., 2019). Interest and awareness are increasing to use medicinal plants and algae for controlling and inhibiting plant diseases caused by pests. For this purpose, almost 2400 plant species have been screened for potential phytoactivity (Khafagi & Dewedar, 2000).

In this review we will discuss both biopesticides active against plant pathogens and biopesticides active against insect pests.

Assessment of plants as biopesticide

Plant derived pesticides are obtained from leaves, roots, barks, seeds, fruits and bulbs. The plant parts are dried and bioactive compounds extracted (Chougule & Andoji, 2016). Different parts of plants are used for making biopesticides and extracts taken for assessing potential activity. (Ahmad et al., 2009). For example, cinnamon essential oil extract from cinnamon bark showed antifungal activity against *Phytophthora colocasiae* which causes acute decline, and up to 100% crop loss. The main component of the oil is cinnamaldehyde. At 0.625 mg/mL, the maximum inhibition of mycelial growth, zoospore germination, and sporulation of the fungus were observed, whereas leaf necrosis due to phytotoxicity was 100% at 1.25 mg/mL (Hong et al., 2021).

Essential oils can be used as biopesticide alternatives to monocrotophos. The eugenol derivative, 4-allyl-2-methoxy-1-(4-trifluoromethyl-benzyloxy)-benzene with a feeding deterrent index (FDI) of 54.14% and the thymol derivative, 2-isopropyl-4-methyl-2-(4-nitrobenzyl) oxy) benzene with an FDI of 53.88% are extracted from clove and thyme essential oils respectively. Both showed as antifeedant agents against the fourth instar larvae of *Spodoptera littoralis* through oral administration for 14 days. This study revealed that the ether compound was more effective than the ester compound regardless of the essential oil (Yan et al., 2021). Commercially available herbaceous plant *Nepeta cataria* extracts are effective repellents against mites, mosquitoes and cockroaches. The essential oil and hydrosol from *Cuminum cyminum* (cumin) seeds, characterized by γ-terpinene-7-al (34.95%), cumin aldehydes (26.48%), and α-terpinene-7-al (12.77%), were evaluated against second-stage juvenile (J2s) root-knot nematodes *Meloidogyne incognita* and *M. javanica* in the soil. The motility, hatching, and survival of J2s was affected after immersion in the essential oil at

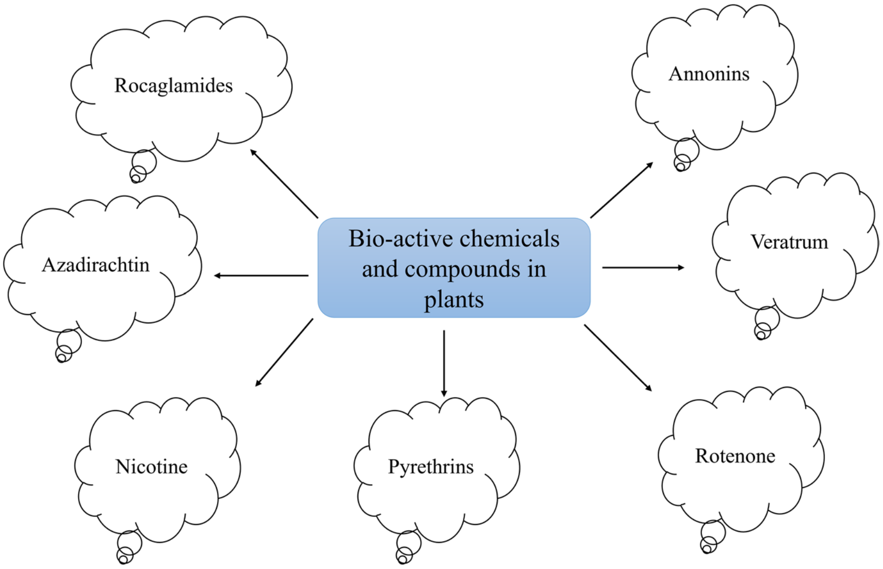

Fig. 1 Bioactive chemical and compounds found in plants that has potential as bio-pesticide

1000 and 2000 µL/L. The lowest numbers of hatched J2s were recorded. More than 70% of paralyzed J2s were recorded after immersion for 48 h, which increased to more than 90% after 96 h (Pardavella et al., 2021).

Azadirichta indica L., *Thuja orientalis* L., *Nicotiana tabacum* L., *Nicotiana rustica* L., and *Melia azedarach* L. aqueous and powder extracts are used as alternatives to synthetic insecticides for the control of *C. maculatus* in stored pulses. Their toxicity was evaluated under specific conditions at concentrations of 0.50%, 1%, 1.5%, 2%, 2.5%, and 3%, and the following was the most effective biopesticide, *N. tabacum*, *A. indica*, and *M. azedarach*. The mortality rate of *C. maculatus* was significantly higher with all aqueous phytochemicals and all *N. tabacum* concentrations as well as powdered *A. indica*. *T. orientalis* recorded lower mortalities with the least number of phytochemicals (Akbar & Khan, 2021). Azadirachtin, a component of NeemAzal, is a plant-based insecticide, which is bio-efficient and biodegradable. Azadirachtin suppresses sugar beet moths (*Scrobipalpa ocellatella*) by reducing feeding, delays in larval and nymphal development, incomplete ecdysis, sterile eggs, deformed pupae and adults, and reduced fecundity. The optimal period to spray azadirachtin was 5–6 days after the moth deposited eggs, and concentrations of 2 and 2.5-ml L^{-1} had a substantial impact on *S. ocellatella* mortality. Thus, defined concentrations of a sugar beet moth insecticide applied at the end of the growing season significantly reduced crop loss (Allahvaisi et al., 2021). The Asteraceae family of plants are used as botanical pesticides as they have effective chemicals for killing and controlling harmful fungi. Bioactive compounds include alkaloids, terpenoids and flavonoids (Ferreira et al., 2013). *Tarchonanthus camphorats* is capable of killing and inhibiting many bacteria (Sunder et al., 2011). Current trends are towards the extraction and use of plant materials for pest control (Villaverde et al., 2016) (Fig. 1).

Assessment of algae as eco-friendly biopesticides

Marine macro-algae (seaweed), are present on the seafloor attached to rocks or boulders, floating over the seawater, or sometimes drifting to shore. Seaweeds are found in the inter-tidal zones of tropical to temperate to cold waters (Coppejans et al., 2009). More than 10.000 species of macro-algae are known. Seaweeds are categorized into three main groups i.e., red (Rhodophyta), brown (Ochrophyta), and green (Chlorophyta), based on pigmentation, morphological, and anatomical features (Guiry & Guiry, 2017). Seaweeds have been used as food, forage, fertilizer, medicine, and other therapeutic applications benefiting human health (Blunden, 1993; Smit, 2004). Marine algae synthesize and emit bioactive compounds as a defence mechanism, which have been identified and isolated (Perez et al., 2016). More than 2700 natural products have been reported. The secondary metabolites belong to terpenoids, alkaloids, phenols, esters, triglycerides, hydrocarbons, isoprenoids, alcohols, fatty alcohols, steroids, and waxy constituents. The largest variety of natural products has been reported from the red algae (Rhodophyta) mainly from genus *Laurencia* (Ioannou & Roussis, 2009). *Laurencia* is a complex genus comprising 383 species, of which 209 are taxonomically accepted (Cassano et al., 2019). The newly discovered *Laurencia karachiana* from Pakistan also possess insecticidal potential (Bibi et al., 2021) enriched with alcohols, fatty acids, sesquiterpenes, diterpenes, and steroids (Bibi et al., 2020).

The insecticidal potential of seaweeds is described (Table 1). Chemical composition analysis of seaweed extracts revealed that halogenated compounds such as triterpenoids and lipophilic compounds such as fatty acids are involved in insecticidal activity (Gressler et al., 2009). Oil-based compounds penetrate insects' bodies through cuticles and respiratory tracts and cause cellular and haemolymph acidosis, which leads to death (Sugiura et al., 2008). *Fucus spiralis* brown algae essential oil has an insecticidal effect against the Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae) (Gressler et al., 2009). Insecticidal efficiency was tested on the pupae and adults using different concentrations of *F. spiralis* essential oils. The activity of the essential oils against adults was higher, with an LD_{50} and an LD_{90} of 0.239 and 2.467 ppm, respectively (Boutjagualt et al., 2022). Gas chromatography–mass spectrometry revealed the presence of borneol (13.13%), hentriacontane (6.13%), bornyl salicylate (5.48%), docosane (6.93%), octacosane (5.62%), heptacosane (7.22%), and limonene (4.9%), which made up the essential oil (Boutjagualt et al., 2022).

Widespread distribution of seaweeds can be utilized as an alternative approach to develop eco-friendly pesticides and repellents against mosquito species (Bibi et al., 2020). Further volatile compounds that are synthesized by seaweeds for their defence against herbivores and predators induce feeding deterrents and toxic effects against agricultural pests (Rovirosa et al., 2013). These antifeedants can be isolated and applied against harmful sap sucking pests and stored grain commodities. Thus, huge biomass of seaweeds, enriched with potential bioactive compounds, is wasted every year along the shore and is the most alternative and safe source of biopesticides that can replace harmful synthetic pesticides.

Mechanism of action of biopesticides

Despite the variety of phytochemical pesticides, the mode of action of all compounds is unknown (Singh, 2017). Plants' bioactive compounds have different

Table 1 Efficacy of plants and algae as a biopesticide against pests

Plants and Algae source	Target pest	Reference
Azadirachta indica	*Aphis craccivora, Amrasca devastans, Sitobion avenae* *Bemisia tabaci,* and *Sciothrips cardamom* (Insects)	(Baidoo et al., 2012; Stanley et al., 2014)
Allium sativum	*Rhizoctonia solani, Colletotrichum* sp., *Staphylococcus aureus, Staphylococcus epidermidis,* (Fungi) and *Spodoptera littorals* (Insects)	(Baidoo & Mochiah, 2016; Suleiman & Abdallah, 2014)
Euphorbia spp.	*Escherichia coli, Salmonella typhi* (Bacteria), *Tribolium castaneum* (Insect) and *Aspergillus flavus* (Fungi)	(Abubakar, 2009; Gayathri & Ramesh, 2013; Mohammadi et al., 2016; Voukeng et al., 2017)
Curcuma longa	*Streptococcus pyogenes, Ralstonia solanacearum, Escherichia coli, Listeria monocytogenes,* and *Bacillus subtilis* (Bacteria)	(Abubakar, 2009; Gayathri & Ramesh, 2013; Mohammadi et al., 2016; Voukeng et al., 2017)
Cinnamomum zeylanicum	*Escherichia coli* (Bacteria), *Bursaphelenchus xylophilus, Meloidogyne* sp., (Nematode) and *Penicillium* spp. (Fungi)	(Nikkhah et al., 2017; Shirurkar & Wahegaonkar, 2012; Zhang et al., 2016)
Zingiber officinale	*Drosicha mangiferae, Trichoplusia binotalis,* and *Necrobial rufipes* (Insect)	(Al-Rahmah et al., 2013)

actions that may be physical or biological towards plant pathogens, insects, nematodes, and interactions depending on the type of compound and the pathogen (Grdiša and Kristina 2013; Aioub et al., 2022).

Mode of action of biopesticides

Plant extracts are lethal or toxic and affect the physiological activities of insect pests like preventing feeding and decreasing oviposition (Chengala & Singh, 2017). Antifeedant plant extracts prevent feeding by making the meal taste bad and the larvae die of starvation. Examples include *M. alternifolia* oil on *Helicoverpa armigera* (Liao et al., 2017); *Gliricidium sepium* methanol extract against coffee Mealybugs (*Planococcus citri* Risso) (Nukmal et al., 2017); and *Polyalthia longifol*ia (methanol extract), *Polyalthia longifolia* (petroleum ether), *Limonia acidissima* (methanol) against *Spodoptera litura* (Arora, 2017). The eco-friendly essential oil of *Ageratina adenophora* has an antifeedant activity of 87.46% against *Plutella xylostella* (L.) (Mayanglambam et al., 2022).

Botanical pesticides have a toxic effect on insects infesting stored products by poisoning the mitochondrion, resulting in electron transport chain disruption and energy production inhibition (Stevenson et al., 2017). The crude phenolic compounds (methanolic extract) of *Acorus calamus* poisons the tobacco cutworm (*Spodoptera litura*) larvae and affect the hormonal balance by decreasing carboxylesterase, which affects the neurotransmitter acetylcholine (Wiwattanawanichakun et al., 2022). Essential oils from *Mentha arvensis* are highly toxic and penetrate the thick, hard exoskeleton, leading to disorders in the biological systems of *Sitophilus granaries* (Renoz et al., 2022). *Thaumastocoris peregrinus* is controlled by toxic essential oil from *Eugenia uniflora* (L.), which affects the hatching and increases the mortality of adults and nymphs (Stenger et al., 2021).

Botanical insecticides harm the pathogen by decreasing or inhibiting its stages of development (Isman, 2017). Essential oils of *Teucrium quadrifarium* and *Boenninghausenia albiflora* have growth inhibitor properties against *Spilarctia obliqua*, causing morphological and physiological effects, leading to a decrease in larval and pupal weight and increased mortality (Tandon & Mittal, 2018). Plant extracts from *Lantana camara*, *Catharanthus roseus*, *Coleus amboinicus*, *Curcuma longa*, and *Alpinia pyramidata* provide toxicity, growth regulator properties, and antifeedant activity towards *Plutella xylostella* Linn diamondback moth (2nd larval instar) (Javier et al., 2019).

Extracted plant metabolites like alcohols, terpenes, alkaloids, phenols and tannins inhibit fungal growth by inhibiting spore germination and development of mycelia, or by degenerating hypha and mycelia (Yoon et al., 2013). The pathogenic fungus *Valsa mali* was affected by wood tar (EC_{50} ranged from 69.54 to 92.81 μg/mL), leading to hyphal breaks, increased cell membrane permeability, and unbalanced enzyme production related to the decrease in pectinase and related genes. (Chen et al., 2022). A series of Michael-type amino derivatives were prepared from xanthatin, a secondary metabolite extract from *Xanthium strumarium*, with antifungal activity and inhibition of mycelium growth on *C. mandshurica* and spore germination against *F. solani* (Zhi et al., 2022). *Uvaria grandiflora* extract (zeylenone) inhibited growth of cucumber powdery mildew, and sporangium formation of *Phytophthora capsica* by destroying the cell wall structure and energy metabolism. Also, zeylenone was toxic to normal cell lines (He et al., 2021).

Similarly, botanical pesticide exposure affects bacterial growth especially Gram-negative organisms through its effect on cellular metabolism like protein synthesis (Djeussi et al., 2013). Pesticide exposure causes microbial death by increasing plasma membrane permeability (Khan et al., 2009). For example, hydroalcoholic extract from *Larrea tridentata* provides bactericidal activity to multidrug-resistant bacteria like *Pseudomonas syringae, Michiganensis, Clavibacter michiganensis* sbsp*.,* especially *Xanthomonas campestris* (Morales-ubaldo et al., 2021). Parthenolide from *Magnolia grandiflora* Linn causes cell death in *Xanthomonas oryzae pv. oryzae* (Xoo) by accumulation of reactive oxygen species, decreased glutathione reductase and increased glutathione peroxidase activity (Xu et al., 2018).

Plant extracts with nematocidal activity inhibits egg hatching and reduces nematode populations (Abd El-Aal et al., 2021; Eldeeb et al., 2022). For example, methanolic extracts of *Anaphalis virgata* and *Anaphalis nepalensis* were tested against root-knot nematodes (Ismail et al., 2021). Extract of *W. indica* roots provide high nematocidal activity towards J2 of *M. incognita* by three isolated compounds i.e., waltherione C, 5′-methoxywaltherione A and waltherione A (Jang et al., 2019).

Some phytochemicals inhibit viral infection by inducing host resistance (Montanha & Moellerke, 2004), inhibiting virus penetration and virus replication (Rajasekaran et al., 2013). Benzosuberene compound extracted from *Cedrus deodara* oils inhibit self-assembly of tobacco mosaic virus (Sharma et al., 2021). The liberation of nucleic acids of watermelon mosaic virus is blocked by *Thuja orientalis* extract, leading to inhibition of multiplication (Elbeshehy et al., 2015).

Nano-biopesticides

Nanopesticides are nanostructures with two to three dimensions between 1 to 200 nm, used to carry agrochemical ingredients. Nano-biopesticides are appealing because of their small size, high surface-area-to-volume ratio, stability, increased effectiveness, improved solubility, mobility, and importantly low toxicity (Fig. 2) (Lade et al., 2019). Toxins released into the food chain by chemical pesticides sprayed directly on plants can cause environmental problems. Pesticides that contain nanoparticle formulations, such as micelles and nano-composites, lower the risk of environmental and health problems (Aioub et al., 2022). Clay-based nanotubes similarly transmit chemical insecticides (Sasson et al., 2007). Nano-biopesticides, like nano-fertilizers, are packaged in carriers that allow for the controlled release of active ingredients to achieve the intended effects in each environment.

The addition of nano-biopesticides to biopolymers improves stiffness, penetrability, crystallinity, thermal stability, solubility, and biodegradability (Manjunatha et al., 2016).

Nano-biopesticides comprising nano-materials that are applied to soils, results in the establishment of mutualistic bacteria that boost plant growth (Lu et al., 2010). Toxicity can be caused by silver-based nanoparticle coatings, which can be reversed by biocompatible coatings, improving the likelihood of seed germination in plants. Nano-emulsions, nano-encapsulates, nano-containers, and nano-cages have recently been described as nano-pesticide delivery strategies for plant protection with

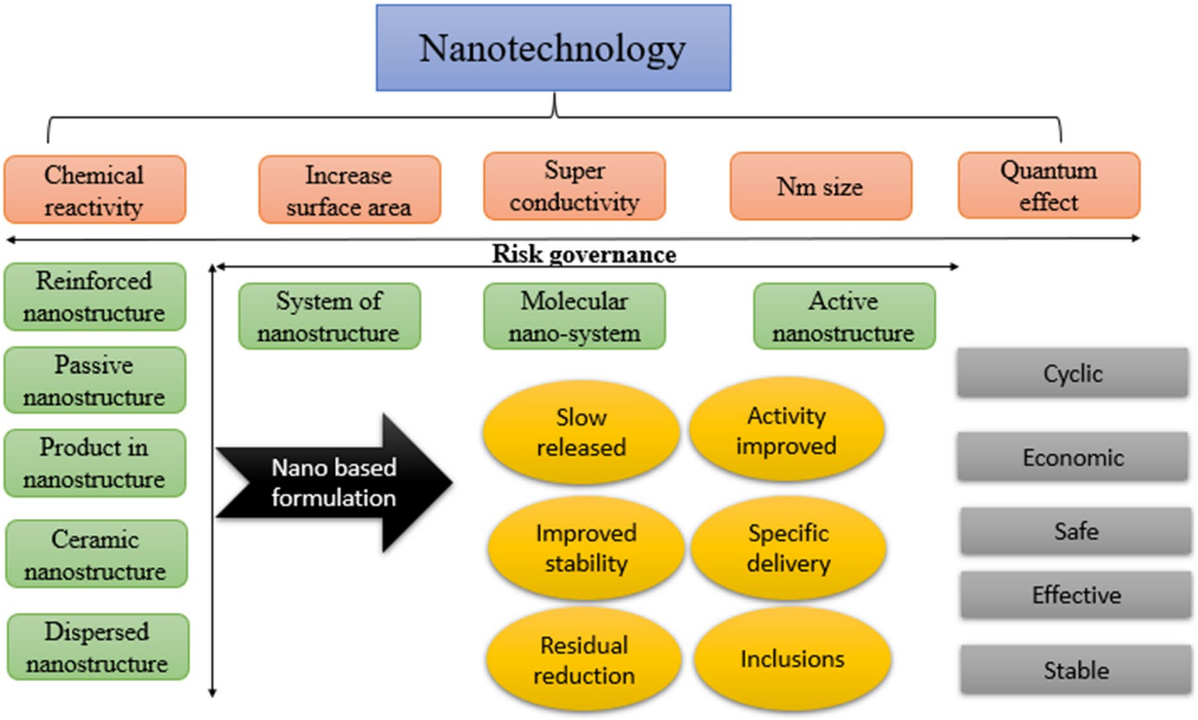

Fig. 2 The importance of nanotechnology for the formulation of nano-based bio-pesticides. This figure is reproduced from Lade et al. (2019)

various capabilities (Bouwmeester et al., 2009; Hazafa et al., 2022). Cationic polymers may adhere to polyanionic surfaces of bacteria, rupture cell membranes, and kill pests. Biopesticides, such as nano-biopesticides, can be used on plants to reduce microbial resistance, but chemicals applied directly to plants are unable to suppress a wide spectrum of bacterial growth (Li et al., 2019). Long amino acid chains including tertiary ammonium groups can be found in nanoparticles. Depending on their structure, these groups may combat a variety of pests and ailments including bacteria (Hazafa et al., 2022; Ng et al., 2014), because of their strong activity in a range of environmental and chemical conditions. Many polymers with this property have been discovered and studied. For example, amphiphilic copolymers, functionalized cationic polycarbonates, poly(amidoamines), polyethylenimine, poly (methyl methacrylates), amino celluloses and chlorinated cellulose acetates are available commercially (Ng et al., 2014).

Plants containing nano-emulsions of essential oils can be employed to reduce insect larval infections. Nano-emulsions from *Tagetes minuta*, *Ageratum conyzoides*, and *Achillea fragrantissima* are used to inhibit the growth of *Callosobruchus maculatus*. The nano-emulsions can be used in fumigation to kill or restrict the formation of eggs and larvae, with treatment ranging from 16.1–40.5 µL/L and 4.5–243 µL/L, respectively (Nenaah et al., 2015). Encapsulation of essential oils can be accomplished with nanoparticles made of liposomes and solid lipids. Inverse gelation and oil emulsion can be used to encapsulate essential oils (Lopez et al., 2012). Encapsulation in liposomes is beneficial against bacteria because the cell membrane is protected from the impact of essential oils (Sherry et al., 2013). However, many forms of nanoparticles are employed for pest control. Microparticles are also employed to keep the effects of essential oils stable. Encapsulation of carvacrol with the cell wall of *Saccharomyces cerevisiae* was conducted with a diameter of 0.5 mL to control the larvae of *Rhipicephalus microplus* with LC_{50} of 0.71 mg/mL. *Saccharomyces cerevisiae* cell wall appears to be beneficial in preserving the low volatility of encapsulated carvacrol, which retains acaricidal action for up to 60 h (Da Silva et al., 2017).

Commercial applications of biopesticides derived from plants and algae

Commercially made pesticides derived from higher plants and algae are biodegradable and eco-friendly. Compounds extracted from biological origins contain chemicals like terpenes, alkaloids, quinines, aldehydes, amino acids, saccharides, and flavonoids. These compounds are ecologically important as they are used commercially for antifeedant, nematicide, insecticide and fungicide products (Souto et al., 2021). From 1939 to 1962, the world focused on synthetic pesticides like 1,1,1-trichloro-2-propanol and 2-bis(4-chlorophenyl)-ethane (Jarman & Ballschmiter, 2012). As these chemicals are harmful and remain in contaminated soil, water and air for long periods and have adverse environmental effects (Multigner et al., 2010).

Formation of commercial biopesticides with algae is simple and low cost, as different varieties of microalgae can be obtained through wastewater (Ranglová et al., 2021). Duckweed (*Lemna minor*), water hyacinth (*Eichhornia crassipes*) and filamentous algae (*Lyngbya wollei*) produce allelopathic compounds that have potential commercial chemical application to inhibit the growth of pests (Fu et al., 2020). Biopesticides are evaluated and checked with the same regulations and rules as synthetic pesticides. Products from plants and algae are required to be prepared in safe environments according to strict guidelines before registration (Wang et al., 2000). It is believed that the commercial market of biopesticides will completely replace the market of synthetic pesticides by 2050 (Damalas, 2018) (Table 2).

Conclusion and future prospective

Synthetic pesticides' quick action makes them the first line of treatment, but their large-scale use has resulted in environmental hazards and the development of resistance. Therefore, environmentally safe plant products with fungicidal and insecticidal properties are a potential alternative. They can be as effective as conventional pesticides when applied as part of an integrated pest management strategy, especially for crops such as fruits, vegetables, nuts, and flowers. Application of chemical pesticides leads to the destruction of beneficial microorganisms and residues may accumulate. Bioactive compounds present in plants

Table 2 Insecticidal activities of marine seaweeds

Marine seaweeds	Extracts Compounds	Pests	Results	Ref
Lyngbya wollei	-	*Escherichia coli, Bacillus subtilis, Salmonella typhi*	Inhibition of growth rate	(Fu et al., 2020; Kumar & Singh, 2015)
Micro and macro algae spp.	-	*Sitobion avenae, Staphylococcus epidermidis*	Inhibition of growth rate	(Asimakis et al., 2022)
Cladophora glomerata	Saturated/unsaturated fatty acids	Mosquito, *Aedes triseriatus*	Larvicidal (LC_{50} 3 – 14 ppm)	(LaLonde et al., 1979)
Laurencia pinnata	Isolaurepinnacin	Azuki bean beetle, *Callosobruchus chinensis*	97% mortality after 24 h	(Fukuzawa & Masamune, 1981)
L. pinnata	Laurepinnacin	Cabbage army worm, *Mamestra brassicae*	Larvicidal	(Fukuzawa & Masamune, 1981)
Plocamium cartilagineum	Monoterpene, Violacene	Tobacco hornworm, *Manduca sexta*	Larvicidal	(Crews et al., 1984)
Chondria armata	Domoic acid	American cockroach, *Periplaneta americana,*	100% mortality at 1 µg/g,	(Maeda et al., 1984)
		House fly, *Musca domestica*	40% adult mortality at 0.1 µg g/ insect	
		German cockroach, *Blatella germanica*	60% adult mortality at 0.6 µg / insect	
Digenea simplex	Kainic acid	American cockroach, *P. americana*	100% adult mortality at 100 µg/ g	(Maeda et al., 1984)
C. armata	Isodomic acid-B	American cockroach, *P. americana*	Strong insecticidal activity	(Maeda et al., 1984)
Polcamium sp.	γ- BHC	Mosquito, *Anopheles gambiae*	0.0096 µg/mL	(Watanabe et al., 1990)
Polcamium sp.	γ- BHC and telfairine	German cockroach, *B. germanica*	Excitatory effect on central nervous system	(Watanabe et al., 1990)
Caaulerpa scalpelliformis	2:8 Methanol acetone	Mosquito, *Ae. aegypti*	LC_{50} 15.85 mg/L	(Thangam & Kathiresan, 1991)
Plocamium telairiae	Aplysia terpenoid A and telfairine	Mosquito, *An. Gambiae*	Neurotoxic effect, convulsion, death	(Bloomquist, 1993)
Caulerpa racemose *C. peltata*	Petroleum ether-acetone	Mosquito, *Ae. aegypti, Cx. quinquefacitatus*	$LC_{50} < 100$ mg/L	(Thangam & Kathiresan, 1996)
Laurencia obtusa	13-Epilaurencienyne	Ant	Knockdown effect	(Iliopoulou et al., 2002)
Jolyna laminarioides	Methanol	Red flour beetle, *T. castaneum*	40% mortality after 24 h	(Rizvi & Shameel, 2006)
P. cartilagineum	Monoterpene Violacene	Cereal aphid, *Schizaphis granium*	92% adult mortality at 100 ppm after 48 h	(Argandoña et al., 2000)
P. cartilagineum	Polyhalogenated monoterpenes	Aphids *Myzus persicae* and *Ropalosiphum padi*	Deterrent	(Argandoña et al., 2002)
Ulva fasciata	1:1 Dichloromethane- methanol	Mosquito, *Culex* sp	60.2% mortality at 6 mg/mL	(Selvin & Lipton, 2004)
Acrosiphonia orientalis	1:1 Dichloromethane-methanol	Mosquito, *Cx. quinquefasciatus*	62.2% mortality at 100 µg/mL	(Manilal et al., 2009)
C. racemose	Alkaloid caulerpin	Mosquito, *Cx. pipiens*	Second instar (LC_{50} 1.42 ppm)	(Alarif et al., 2010)

Table 2 (continued)

Marine seaweeds	Extracts Compounds	Pests	Results	Ref
C. scalpelliformis	Chloroform	Cotton bug, *Dysdercus cingulatus*	(LC_{50} 256 μg /L)	(Rajesh et al., 2011)
Laurecia papillosa	Acetogenin	Red flour beetle, *Tribolium confusum*	LD_{50} 0.21% after 6 h	(Abou-elnaga et al., 2011)
C. prolifera, C. serrulata *Padina pavonica, Cystoseira myrica, Nitophyllum punctatum*	Dried ground sample	Mosquito, *Culex pipiens*	Prolonged larval duration	(Elbanna & Hegazi, 2011)
Padina pavonica	Chloroform, benzene	Red cotton bug, *D. cingulatus*	Prolonged nymphal duration	(Sahayaraj & Kalidas, 2011)
Lobophora variegata		Mosquito sp., *Ae. Aegypti, Cx. quinquefasciatus*	$LC_{50,}$ 70.3 μg /ml, 79.4 μg /ml	(Kumar & Sujith, 2011)
Sargassum wightii	Methanol	Mosquito, *An. sundaicus*	Prolonged developmental stages, reduced adult emergence	(Kumar et al., 2012)
Ulva fasciata, U. lactuca	Methanol, chloroform	Red cotton bug *D. cingulatus*	Reduced longevity, fecundity, eggs hatchability, whole body weight	(Asha et al., 2012)
C. scalpelliformis	Chloroform	*Spodoptera litura* Red cotton bug *D. cingulatus*	Repellent effects with black colouration in insects body	(Kombiah & Sahayaraj, 2012)
Sargassum tenerrium	Benzene	Cotton Pest, *D. cingulatus*	Anti-insect activity (LC50 0.009%)	(Sahayaraj & Jeeva, 2012)
Laurencia dendroidea	Sesquiterpene, Elatol	Mosquito, *Ae. aegypti*	LC_{50} 10.7 ppm	(Bianco et al., 2013)
C. racemose	Ethanol	Mosquito, *Ae. Aegypti,*	(LC_{50} 0.05 μg /mL),	(Ali et al., 2011)
		Mosquito, *Cx. quinquefasciatus*	(LC_{50} 0.05 μg /mL),	
		Mosquito, *An. stephensi*	(LC_{50} 0.06 μg /mL)	
P. cartilagineum	Polyhalogenated monoterpenes	Tobacco budworm, *Heliothis virescenes,*	Anti-insect activity	(Rovirosa et al., 2013)
Bryopsis pennata	Chloroform	Mosquito, *Ae. aegypti*	Larvicidal (LC_{50} 82.5 μg/mL) with morphological abnormalities	(Yu et al., 2015)
Jania rubens	Hexane	Mosquito, *Ae. aegypti*	Larvicidal (60% mortality after 24 h at 40 mg/ml)	(Jagadeesan et al., 2015)
L. obtusa	halogenated sesquiterpene (-)-elatol and (+)-obtusol	Mosquito, *Ae. aegypti*	Larvicidal with reported destruction in the intestinal epithelium	(Salvador-Neto et al., 2016)
B. pennata	Methanol	Mosquito, *Ae. aegypti* (L)	Larvicidal LC_{50} 156 μg/ml	(Ahmad et al., 2016)
		Ae. albopictus	LC_{50} 177 μg/ml,	
		Mosquito, *Ae. aegypti* (L)	Adulticidal LC_{50} 17.5 μg/mL	
		Ae. albopictus	LC_{50} 35.4 μg/mL	
P. cartilagineum	Mortensene, Dibromomertensene, dihydromertensene	Tomato moth, *Tuta absoluta,* Cereal aphid, *Schizaphis graminum*	Lavicidal, adulticidal	(Argandoña et al., 2000)

Table 2 (continued)

Marine seaweeds	Extracts Compounds	Pests	Results	Ref
L. brandenii	Fraction	Rice weevil, *Sitophilus, Oryzae*	LD_{50} 3.7 mg/cm^2	(Manilal et al., 2011)
Dictyota dichotoma	3:1 Ethanol and water	*Ae. aegypti*	LC_{50} 0.068 mg/mL	(Beula et al., 2011)
L. papillosa	Acetogenin, (12E)-cis maneonene-E	Mosquito, *Culex pipiens pallens*	Second instar LC_{50} 30.7 µg/mL	(Abou-elnaga et al., 2011)
Chondria dasyphylla	Ethyl acetate fraction	Mosquito, *An stephensi*	LC_{50} 10.6 µg/mL	(Khanavi et al., 2011)
Padina minor	95% Ethanol	Mosquito, *Ae. aegypti*	LC_{50} 50.8 mg/mL	(Bantoto & Dy, 2013)
Gracilaria corticata	Ethanol	Mosquito, *Ae. Aegypti*	LC_{50} 0.08 µg/mL	(Ali et al., 2013)
		Mosquito, *Cx. quinquefasciatus*	LC_{50} 0.09 µg /mL	
		An. stephensi	LC_{50} 0.09 µg/mL	
Seaweeds	Extracts	Mosquito, *Aedes aegypti* (L)	Larvicidal	(Hira et al., 2017)
Turbinaria ornate	Hexane	Mosquito, *Aedes aegypti* (L)	Larvicidal LC_{50} 1.38 µg/mL	(Sowmiya et al., 2017)
L. nidifica	Laurinterol	Maize weevil, *Sitophilus zeamais,* Termites	Repellent	(Ishii et al., 2017)
S. cristaefolium, C. Agardh	Methanol	Tobacco caterpillar, *Spodoptera litura* Fab	Antifeedant, larvicidal, growth inhibitor	(Gowthish et al., 2018)
L. intricata	(+)-Cyclocolorenone	Maize weevil, *S. zeamais,* Termites	Repellent	(Ishii et al., 2019)
S. polycystum	Silver nanoparticles	Mosquito, *Aedes aegypti*	LC50 0.03 µg/mL after 72 h	(Vinoth et al., 2019)
		An. stephensi	LC50 1.15 µg/mL	
		Cx. quinquefasciatus	(0.23 µg/mL)	
C. veravalensis	Tetradecanoic acid, 10, 13-dimethyl-, methyl ester	Cotton pest, *D. cingulatus*	Growth, development and oviposition	(Sahayaraj et al., 2019)
Gracialria filiforms	Fraction polysaccharide	Mosquito, *An. stephensi*	LC_{50} 0.23 µg/mL	(Venkatesan et al., 2019)
Turbinaria conoides	Fraction polysaccharide	Mosquito, *Ae. Aegypti*	LC_{50} 0.17 µg/mL	(Venkatesan et al., 2019)
Enteromorpha compressa	Fraction polysaccharide	Mosquito, *Cx. quinquefasiatus*	LC_{50} 0.1117 µg/mL	(Venkatesan et al., 2019)
Gracilaria edulis	Methanol	Tobacco cutworm, *Spodoptera litura*	53% larval mortality after 72 h with growth inhibiting effects	(Gowthish & Kannan, 2019)
Jania rubens	Hexane	Green peach aphid, *Myzus persicae*	Antifeedant	(Bibi et al., 2020)
		Mosquito, *Ae. aegypti* L	Neurotoxic (EC_{50} 37.4 µg/mL), Larvicidal (LC_{50} 32 µg/mL), 24 h	(Bibi et al., 2020)
Laurencai karachiana	Hexane	Mosquito, *Ae. aegypti* L	Larvicidal LC_{50} 89 µg/mL, 24 h	(Bibi et al., 2020)
Asparagopsis taxiformis	Dichloromethane	Cowpea weevil, *Callosobruchus maculatus*	LC_{50} 1.14 after 24 h, reduced oviposition	(Bibi et al., 2021)
Gracilaria follifera	Hexane	Mosquito, *Ae. aegypti* L	Larvicidal LC_{50} 76.8 µg/mL, 24 h	(Bibi et al., 2021)

Table 2 (continued)

Marine seaweeds	Extracts Compounds	Pests	Results	Ref
Chaetomorpha antennina	Isolated fraction 5 enriched with methyl ester of chloroacetic acid	Tobacco cutworm, *S. litura*	LC_{50} 38.73 ppm, reduce haemocyte count (69.8%) and some major defence enzyme	(Chanthini et al., 2021)
Lobophora variegata	Silver nanoparticle	Tobacco cutworm, *S. litura*	Affect development, moulting, morphology	(Kitherian et al., 2021)

and algae have pesticidal effects. Biopesticides derived from them are eco-friendly, safe and beneficial for the environment. Therefore, development of eco-friendly plant and algal-based pesticides is needed for pest management with minimal environmental impact. Biopesticides along with fewer application constraints, enhanced resistance management potential, and environmental safety make them more efficient. This supports the United Nations Development Program's 2030–2050 objectives, with the preservation of the global climate, which protects life on land and in water. Thus, a clean environment is secured where with adequate food for every human being, a reduction in poverty, and enhanced scientific and cultural development.

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Ammar AL-Farga: Collected and summarized the results and revise the final manuscript.

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