

Potential Application of Nanoemulsion in Agriculture: A Current Perspective

R.Thirumalaisamy¹, S.Nimithap², S.Harini³, Rathika Rajiniganth⁴, S.Haritha⁵, Kalandar Ameer⁶, P.Vadivel⁷, T.Selvankumar^{2*}

¹Department of Biotechnology, Sona College of Arts and Science, Salem (Dt.)-636 005, Tamil Nadu, India

²Department of General Medicine, Saveetha Medical College & Hospital, Saveetha Institute of Medical and Technical Sciences (SIMATS), Thandalam, Chennai- 602105, Tamil Nadu, India

³Department of Chemistry, Bharathiar University, Coimbatore (Dt.)-641 046, Tamil Nadu, India

⁴PG & Research Department of Biotechnology, Mahendra Arts & Science College (Autonomous), Namakkal-637 501, Tamil Nadu, India

⁵Department of Biotechnology, Stella Maris College (Autonomous), Chennai – 600 083, Tamil Nadu, India

⁶Department of Biochemistry, Faculty of Medicine, AIMST University, Bedong-Kedah 08100, Malaysia

⁷Department of Chemistry, Salem Sowdeswari College, Salem -636 010, Tamil Nadu, India

ABSTRACT: The growing global population is driving the stipulation for food and agronomical resources. The application of traditional agrochemicals in the agriculture sector has wide-ranging consequences on both organisms and the environment. Prospects in formulating nanoemulsions used as nano delivery systems for agrochemicals in fields, crop protection, and farm animal management by improving animal and plant efficiency in agriculture. This review places emphasis on bio nanoemulsion formulation for different agricultural applications such as pesticides, fungicides, acaricides, insect and tick repellents, herbicides, and nematicides, which reduce toxicity and, in turn, improve environmental sustainability. Overall, nanoemulsion paves the way to more efficient, eco-friendly and reliable implementation in agronomics. The targeted active substance is advantageous using a method of nanoemulsion due to their unique size to surface area ratio. This allows better penetration through plant cuticles and insect agrochemicals. The controlled release mechanisms inherent in nanoemulsion systems can minimize the environmental impact of agrochemicals. By allowing for targeted application at lower dosages, nanoemulsions protect active ingredients from disintegration due to factors such as light and heat fluctuations. This stability ensures that the agrochemicals remain effective over longer periods, enhancing their usability in various agricultural settings.

KEYWORDS: Nanoemulsion; Agriculture; Herbicide; Pesticide

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1. INTRODUCTION

Nanoemulsions are also known as ultrafine emulsions and mini-emulsions due to their lower droplet size (20-200nm) [1]. Because of the less particle diameter and relatively high surface tension, which reduce the interfacial area, and the NEs droplet appear to be spherical. [2] Water, oil and surfactant are three major constituents of nanoemulsion. In a nanoemulsion one aqueous solution is distributed as tiny; globular droplets into

another aqueous medium; however, only 5-10% of the surfactants are needed [3]. Nanoemulsion are of three types: oil in water (O/W), water in oil (W/O), and bi-continuous. Further, the system is obtained when the oil and aqueous phase are separated by the surfactant layer. Two immiscible phases-oil or organic and water phase that are present in a nanoemulsion system-are separated by surface tension induces by surfactants. Figure 1 depict nanoemulsion

*Corresponding Author: selvankumar75@gmail.com

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with biological activity utilized for agricultural practices

Agrochemicals are primary tool used in modern agriculture to combat agricultural pests and illnesses. At the same time, prolonged and heavy usage of these substances has led to adverse effects on non-target organisms, lower food safety, resistance development in certain species, and environmental contamination [4, 5,6]. Applications of nanofertilizers lead to maximize nutriment usage effectiveness in crop yield, and to solve these concerns the use of biological pesticides and the creation of nano-pesticides have developed as essential study tools [7, 8, 9, 10]. The use of nanoemulsions (NEs) with desired physio-chemical properties as pesticide delivery vehicles has received a great deal of research [11, 8, 12]. Colloidal dispersions, which are miscellaneous systems with the internal phase distributed into a steady medium, are among the most useful technique.

Nanoemulsions (NEs) are self-emulsifying colloidal systems that are disseminated in a liquid media and typically have an inner phase <100 nm [13]. Certain physicochemical qualities, like as stability and bioavailability, are improved by this property of NE. Actually, because of the interior phase's modest size, the system is able to avoid issues caused by gravity, such as creaming or sedimentation. Furthermore, the appropriate developing and perforation of the active chemicals are encouraged by the lower surface and high interfacial tensions [14]. The benefits of colloidal nanoformulation have recently created some enticing opportunities for improving agricultural technologies. According to industrial agriculture estimates, over 70% of typical pesticides are ineffective because they must be used more frequently and at larger doses to achieve the best results. Bio-efficiency plays a crucial role in determining environmental outcomes through various processes such as leaching, volatilization, and runoff.

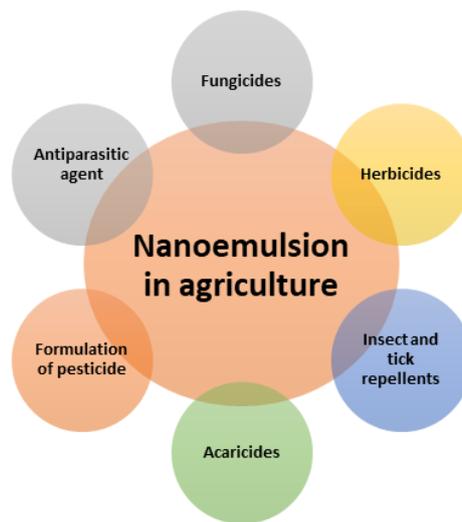


Figure 1: Nanoemulsion with biological activity utilized for agricultural practices

Over the last few decades, good physico-chemical stability, increased biodegradability, nontoxicity, and cost effectiveness have all been achieved with the development of nanoemulsion-based pesticides. The development of effective pesticide formulations based on nanoemulsions is highly desirable for this reason. Nanoemulsions offer numerous advantages when used as pesticides. Thus, the goal of the present study is to assess what is already known about the application of nanoemulsions in agriculture for managing insect pests and to investigate the possible

applications of this cutting-edge technology in entomology.

The main objectives of this review are to investigate the possible uses of nanoemulsions in agriculture, highlighting their function as novel agrochemical and bioactive ingredient delivery methods. The efficacy of pesticides, herbicides, and fertilizers is increased by the special physicochemical characteristics that nanoemulsions provide, such as nanoscale droplet size, increased solubility, stability, and bioavailability. The purpose of this review is to

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demonstrate how precise targeting and controlled release mechanisms of nanoemulsions might reduce environmental contamination. It also discusses the potential for incorporating nanoemulsions into sustainable agriculture methods in the future while addressing present issues with their large-scale production and regulatory compliance.

2. Nanoemulsion Formulation Methods

Nanoemulsion formulation techniques are important since they directly affect the final product's characteristics and functionality. When compared to traditional emulsions, nanoemulsions, which have droplet sizes between 20 and 200 nm, are more stable, bioavailable, and effective. The droplet size, polydispersity index (PDI), and overall stability are all significantly influenced by the formulation process selection, whether it be low-energy or high-energy. High-energy techniques, such as ultrasonication and high-pressure homogenization, use strong mechanical forces to separate the water and oil phases, producing more homogenous and tiny droplets [15-18]. These techniques enable the quick creation of stable nanoemulsions by achieving high energy densities [19-22]. For example, high-pressure homogenization is frequently employed because it uses hydraulic shear and turbulence to create nanosized emulsion in lesser droplet size less than 1nm. In comparison, low-energy methods like phase inversion temperature and spontaneous emulsification can be more economical and use less mechanical energy [23-27]. They frequently call for greater surfactant concentrations, though, which could cause issues with toxicity and the environment. In the end, choosing the right formulation technique is crucial to maximizing the properties of nanoemulsions for particular uses in the food, medicinal, and agricultural sectors. The nanoemulsion strength varies on their preparation method. They can be created using high-energy inputs or surfactants, sometimes combining both approaches [28]. The two main fabrication systems for nanoemulsions are low-energy and high-energy methods [29].

2.1 High shear homogenization

High-shear homogenization is essential for creating a nano-based emulsion. This procedure yields a nanoemulsion with extremely small particle sizes, sometimes as tiny as 1 nm, by employing a heavy-compression or piston

homogenizer [30]. The process involves forcing a combination of water, oil, and surfactant(s) through a narrow orifice ranging from 5–10 mm [31], because of the narrow gap, the pressure on the droplets can rise to several thousand bars. These droplets are subjected to very high shear forces, causing them to break into smaller fragments [32]. Basically, the compound is moved through the homogenizer 15–20 times to ensure the droplet size is stabilized.

2.2 Micro fluidization

Microfluidization is a distinctive mixing process that utilizes a device known as a microfluidizer. This technique employs high pressure to propel the medication through the interaction chamber, resulting in the creation of extremely small, micron-scale molecules. For obtaining the appropriate particle size, the procedure is performed several phases, ensuring a uniform nanoemulsion. Fibers are broken down by a microfluidizer which works by applying high pressure from a pump combined with tangential forces. The suspension of fiber is introduced into the intake and propelled via a narrow, Z- or Y-passage at high pressure. As a result, the suspension speeds up by generating a high shear rate that effectively disintegrates the fibers [33].

2.3 Phase Inversion Temperature

This process involves creating dispersions during a transition by altering the temperature, meaning the resulting nanoemulsions do not need any external force. This method is also known as the persuasive approach, which is divided into four stages: The initial step involves changing a particular variable, such as temperature or another value. The next stage involves altering several variables, including formulation and temperature. The tertiary stage implies transforming the low inner phase emulsion into the external phase. The final stage stabilizes the system by forming aqueous crystals, achieving stabilization of the nanodroplets [34]

2.4 Spontaneous Emulsification

When insoluble fluids in non-equilibrium conditions interact creates spontaneous emulsification. This reaction occurs due to chemical potential gradient between the phases, which, under specific condition, can lead to regressive free energy values during emulsification. The production of

nanoemulsions involves three steps: Initially, it entails the formation of organic solutions composed of hydrophilic and miscible surfactants in a liquid medium. Subsequently, the emulsion undergoes a transformation of the aqueous phase from the organic phase under

magnetic conditions. At final phase, heating procedure removes the organic solvent present. The nanoemulsions produced typically have a size range of 50–100 nm [35]. Figure 2 depict various potential nanoemulsion applications in agriculture.

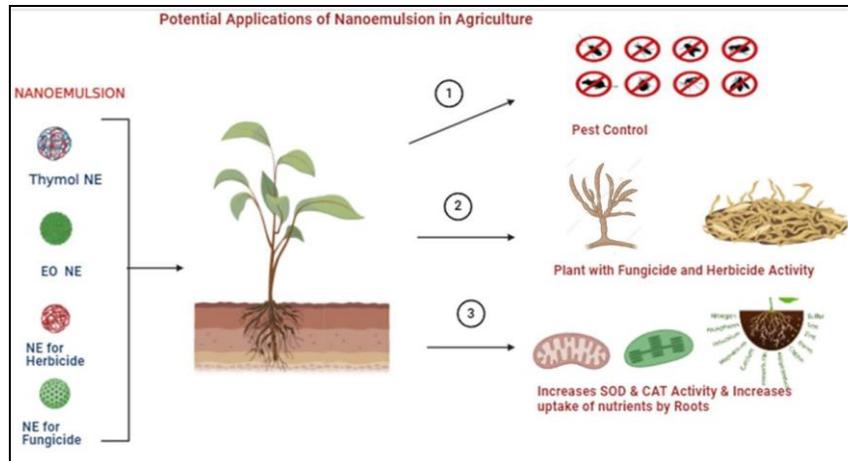


Figure 2: Various potential nanoemulsion applications in agriculture

3. Nanoemulsion as pesticides

An important development in agricultural techniques is the use of nanoemulsions as pesticides, which provide a more efficient and sustainable substitute for conventional formulations. Because of their tiny droplet sizes (20–200 nm), nanoemulsions improve the solubilization, bioavailability, and stability of active substances, increasing their effectiveness against illnesses and pests. Researchers have shown improved insecticidal and antifungal effects by adding natural oils like citronella and neem to nanoemulsion compositions. The capacity of nanoemulsions to lessen the environmental impact of traditional pesticides is one of its main advantages. Conventional formulations frequently cause substantial runoff and lingering ecological harm. On the other hand, sustainable farming methods can be promoted by creating nanoemulsions that are less damaging to non-target creatures and biodegradable [36]. Moreover, nanoemulsions' controlled release characteristics reduce treatment frequency, which lowers the total amount of pesticide used. According to research, insecticides based on nanoemulsions have better adhesion and penetration to plant surfaces, which improves the results of pest management. Furthermore, the addition of surfactants to these formulations improves their dispersibility and stability, enabling consistent administration. All things considered, the

creation of insecticides based on nanoemulsions has enormous potential to boost agricultural output while lowering environmental hazards.

Pesticides are compounds, either biological or chemical, that are applied to crops, wood, and other vegetation in order to eliminate, resist, repel, attract, sterilize, or control pests that cause harm or hinder growth. Pesticide nanoemulsion formulations are composed of active chemicals integrated with nanoemulsion to protect crop from diseases that affect agriculture productivity. Based on the organisms they target; these pesticide kinds have been grouped. Ideal pesticide composition includes active ingredients designed to eliminate weeds (herbicides), destroy fungus (fungicides), control insects such as snails and slugs (insecticides), etc.

The following are the key objectives of formulations of nanopesticides:

- (a) To make poorly soluble active compounds more soluble.
- (b) To deliver the active ingredient in a controlled or targeted manner and/ or safeguard it from early degradation [37].

For instance, a distinct nanoemulsion with the necessary hydrophilic–lipophilic balance (HLB) values of 11.2 and 14.8 for andiroba and copaiba oils has been developed for use against *Aedes aegypti*. The surfactant hydrophilic lipophilic

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value was close to the system's rHLB oil, the nanoemulsions were shown to be stable [38,39]. This study has clearly demonstrated that the steady nanoemulsion was created when the surface active agent HLB value was comparable to the system's oil's rHLB. The contact point of leaves has decreased and their wettability has increased due to the presence of surfactants. Research has indicated that an increased surfactant concentration in pesticides does not guarantee an improved the contact angle on upper and lower surfaces of the leaves. The type of the surfactants may cause variations in the ideal wetted area and contact angle [40]. For specific, beneficial uses, the ideal concentration of surfactant can provide the required particle size, stability, viscosity characteristics, and antibacterial activity.

Thymol NE was produced and characterised by Kumari et al., (2018) [40] by utilizing a Quillaja saponin as a natural detergent. The pustular infection in soybeans is caused by bacterium *Xanthomonas axonopodis* pv. *Glycine*. The researchers targeted against this disease using the nanoemulsion antibacterial action. Thymol NE exhibited potent antibacterial activity, and in the 0.02–0.06 (v/v) concentration range of NE, no bacterial colony was found.

Using oil phase laurate and a blend of surfactants, polyoxyethylene 3-lauryl ether (PLE) and alkyl polyglycoside (AL), the study described the production and characterisation of oil-in-water nanoemulsions (NEs). An insoluble chemical called β -cypermethrin was added to the nanoemulsions in order to assess their possible uses. For the first formulation, the laurate/AL:PLE ratio was 10:5:85, and for the second, it was 20:6:74. It was observed that there were no significant variations in droplet size between the formulations with and without β -cypermethrin when comparing the nanoemulsion with a higher concentration of laurate, that had droplet size approximately 200nm was compared with a lower concentration of laurate, which had an average diameter of 110nm[41]. Additionally, the β -cypermethrin-loaded nanoemulsion retained its homogenous and single-phase appearance even after dilution. Nevertheless, dilution was found to enhance droplet size. Consequently, on hydrophobic surfaces, the diluted nanoemulsion showed enhanced wetting and spreading characteristics.

Previous research study examined the production and description of neem oil nanoemulsion and assessed how the inclusion of two different non-ionic surfactants such as alkyl polyglucoside and naturally based polysorbate increased the stability of the NE. Biological action against two significant pests of stored products was assessed using neem oil NE: *Sitophilus oryzae* and *Tribolium castaneum*. All of the nanoemulsions displayed droplet sizes between 200 and 600 nm, and the formulation with the highest percentage of non-ionic surfactants had smaller droplets than the formulations with the same surfactant composition but lower concentration [42]. The viscosity of the NE increased as non-ionic surfactants were added. After two days of treatment, all pests are treated with 1% NE show 100% eradication, with the exception of the NE that caused 74% and 85% elimination of *S. oryzae* and *T. castaneum*, respectively, due to its larger droplet size of 507 nm. Comparing all NEs to free neem oil and Neemix®, however, revealed stronger harmful effects against both pests.

The generation and characterization of neem oil nanoemulsions (NEs) were examined in a prior study, which also assessed how the stability of these emulsions was improved by the inclusion of two non-ionic surfactants: alkylpolyglucoside and a naturally occurring polysorbate. The efficacy of neem oil NEs against *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst), two significant pests of stored goods, was evaluated. The formulation with the highest percentage of non-ionic surfactants showed smaller droplets than those with the same surfactant composition but lower concentrations [43]. The droplet diameters of all the NEs varied from 200 to 600 nm. The viscosity of the NEs rose with the addition of non-ionic surfactants. With the exception of one formulation that caused 74% mortality in *S. oryzae* and 85% mortality in *T. castaneum* due to its bigger droplet size of 507 nm, all pests exposed to a 1% NE concentration died after two days of treatment. The NEs showed noticeably greater insecticidal activities against both pest species as compared to both free neem oil and Neemix®.

Nanoemulsions stability was shown to be highly dependent on the emulsification process, as stated by the authors. Compared to NEs that diluted the emulsifier agent in the aqueous phase, NEs that diluted it in the organic phase

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demonstrated greater stability. Furthermore, the organic phase containing the emulsifier was added to aqueous phase to form most stable NE. The NE displayed a 166 nm droplet size and a 0.16 PDI.

A previous study used an extract from the apolar fraction of *Manilkara subsericea* fruit to examine the insecticidal efficacy of a nanoemulsion against *Dysdercus peruvianus*. The finest oil phase, according to the study, is octyldodecyl myristate, which can dissolve an equivalent amount of the apolar extract at a 1:1 weight-to-weight ratio. Five percent apolar extract, five percent surfactants, five percent octyldodecyl myristate, and eighty-five percent water are made up the optimal emulsion. In comparison to the extract-free nanoemulsion, which had a droplet size of 57 ± 0.3 nm and a zeta potential of -59.6 ± 4.1 mV, the extract-containing nanoemulsion had a lower zeta potential (-47.4 ± 3.2 mV) and a smaller mean droplet size (155.2 ± 3.8 nm). The death rate of insects treated with the extract-containing nanoemulsion rose from $12.23 \pm 0.58\%$ on the first day of treatment to $44.43 \pm 6.66\%$ after 30 days of exposure [44]. Notably, the extract-containing nanoemulsion did not cause mouse death or reduce acetylcholinesterase activity, suggesting that it is safe for non-target organisms.

O/W NEs entrapping tebuconazole were created by [45] utilising Tween 80 or AG54 surfactant consisting of amphiphilic components blend of both non-ionic and anionic parts. The phase equilibrium region of the aqueous phase, organic phase, and surfactant was found to be 0.01–0.23, 0.49–0.90, and 0.07–0.49, respectively, based on a pseudo-ternary diagram. Both NEs' viscosities exhibited the same behaviour and were dependent on the aqueous phase percentage. As the aqueous phase concentration increased from 4% to 30% by weight, the viscosity decreased by a factor of four, whereas it increased when the concentration rose from 30% to 50% by weight. Nevertheless, the viscosity of the nanoemulsion was set with Tween 80 was higher than that of the nanoemulsion stabilized with AG54. Nanoemulsion containing Tween 80 had droplet sizes of 9 ± 1 nm, which did not change when aqueous phase concentration rise from 1 to 50 per cent. On the other hand, NE made with AG54 exhibited a significant influence on the content of the aqueous phase up to 20 weight percent.

Nevertheless, additional rises in the aqueous phase percentage had little effect on the size droplet that stayed at approximately 250 nm.

Several studies have emphasized the use of various polymers as carriers in the development of controlled release agrochemical nanoemulsions. For instance, biodegradable polyurethane made of castor oil was loaded with avermectin and cyhalothrin, and the properties of its release from the carrier were examined. The results exhibited that the release of avermectin was greatly accelerated by both acidic and alkaline conditions, reaching almost 100% release as opposed to only 72% under neutral conditions. On the other hand, the commercial product released cyhalothrin over a period of 60 hours, whereas the nanoemulsion's release rate was far slower, spanning 180 hours [46].

There are numerous instances of systems that have the potential to be applied in agriculture; yet, much effort needs to be done before these ideas can become products for crop safety. Nanoemulsion should be applied to biologically active insecticides in order to efficiently eliminate plant diseases. Common pesticide nanoemulsion formulations are functional compounds that have the ability to kill weeds (herbicides), insects including snails and slugs (insecticides), fungus (fungicides), mites or ticks (acaricides), and nematodes (nematicides). Table 1 representing various nanoemulsion formulations utilized for pesticidal agricultural applications.

4. Nano emulsions as Acaricides

One intriguing approach to pest management, especially for reducing dangerous mite populations, is the creation of nanoemulsions as acaricides. Traditional chemical acaricides frequently provide serious health and environmental hazards; as a result, using nanoemulsion formulations made from natural sources, like plant oils, is becoming more popular. The effectiveness of nanoemulsions containing essential oils like citronella and tea tree, as well as neem and garlic oils, against a variety of tick and mite species has been shown in recent studies. By improving the stability and bioavailability of active substances, nanoemulsions improve penetration and effectiveness against certain pests [54]. Abamectin formulations in nanoemulsion form, for instance, have demonstrated better

acaricidal efficacy than traditional emulsions, successfully lowering the population density of *Tetranychus urticae*. Nanoemulsions small droplet size (usually less than 100 nm) improves adherence to plant surfaces and raises the possibility of coming into touch with pests. Furthermore, by reducing the environmental impact, the use of essential oils in formulating

nanoemulsion not only offers efficient pest control but also supports integrated pest management techniques [55]. This creative method demonstrates how nanoemulsions can be used as a sustainable substitute for synthetic acaricides, providing improved efficacy while fostering environmental safety.

Table 1 - Various nanoemulsion formulations for pesticide applications in agriculture

Nano emulsion formulation for pesticide	Composition	Application	Reference
Nano emulsion of biphenthrin emulsion in water	Mixing of biphenthrin, monododecylphosphate potassium, dimethylbenzene, fatty alcohol polyoxyethylene ether AE0-3, ethylene glycol and water glut.	This NE is used in field to kill flies. It has high stability after five and more stability.	[47]
Nanoemulsion of pesticide in water	The mixture consists of pethoxamid, polyoxyethylene emulsifying agent, thickener, and preparing method there of garagard, solvent (d-limonene, repefral or propene carbonate), anti-freezing agent, anti-foaming agent and deionized water	Promoting soybean plantation growth by invading grassy weeds and broadleaf	[48]
Nanoemulsion of insecticide	A mixture of pleocidin, egg yolk lecithin, matrine, nano titanium oxide, Tween-80, cyhalothrin, soybean oil, n-butanol, avermectin and griseofulvin.	NE product is applied to field as insecticide.	[49]
cyfluthrin nanoemulsion	liquid white beeswax, Beta cyfluthrin, Span-80, Tween-80 and surplus water	Product is applied as pesticide in field. The NE has size of 69-150nm	[50]
Nanoemulsion of a slow-controlled-release insecticide	A combination of water-insoluble agrochemicals such as cyhalothrin, avermectins and polyurethane is used as carrier	Product generate controlled release of pesticide, has enhanced scattering capacity, stability and bioavailability.	[51]
Avermectin Nanoemulsion	A combination of avermectin, organic solvent (methylene dicarbamate), stabilizer (2, 6-toluene di-tert-butyl phenol, emulsifier (tristyrylphenol polyoxyethylene ether, oxygen propylene ether), butylhydroxy anisole (BHA) and water	Effectively targets Lepidoptera larvae on brassicaceous vegetables, has up to 60% efficiency against wild cabbage pest like cotton red spider.	[52]
Methidathion nanoemulsion	A mixture that includes methidathion, toluene as an organic solvent, emulsifiers (Arlacel-60 and Tween-80), co-solvents (PEG-200 or PEG-600), antifreeze agents (ethylene glycol, propane diols, or glycerine, either individually or in combination), water, thickeners (two stearates of hydroxyethyl cellulose, ethyl hydroxyethyl cellulose), and a silicone-based antifoaming agent	The product produces methidathion nanoemulsion with low toxicity and high stability.	[53]

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In order to ensure the existence of various agricultural and decorative plants in greenhouses, mite management is economically significant. Extensively used traditional pesticides include mitochondrial electron transport inhibitor-acaricides (fenazaquin, fenpyroximate, pyridaben and tebufenpyrad) organotin compounds, and pyrethroids. Despite their high efficacy, their usage has been restricted because of non-target, environmental hazards, toxicity nature to humans also emergence of pest resistance. These problems have brought attention to the necessity of researching fresh approaches to pest control. When it comes to acaricide products, botanical pesticides also appear to be a good substitute for synthetic ones. Specifically, it was shown that essential oils (EOs) are the primary natural sources of chemicals with acaricidal activity.

Dos Santos et al., 2017 [56] reported the effectiveness of using cinnamon essential oil (EO) to control ticks on cattle. In fact, both in vitro and in vivo testing were used to assess this EO against *Rhipicephalus microplus*, an Asian blue tick infects dairy cows. The authors also created NEs and nanocapsules. They proved to be extremely helpful in harnessing the acaricidal properties of cinnamon essential oil. Actually, at a concentration of 0.5%, nanoencapsulated EO demonstrated effectiveness 10 times lesser than that of pure EO (5%). As a result, R. microplus infestation, oviposition, and fertility were all decreased by such nanosystems at a concentration of 0.5%. Actually, the stabilisation, protection, and continuous release of the active substance were all improved by the encapsulation of essential oils.

Nanoemulsion (NE) and emulsion formulations of garlic (*Allium sativum* L.) essential oil demonstrated significant acaricidal effects against *Tegolophus hassani* (Keifer) and *Aceria oleae* (Nalepa), two eriophyid olive mites determined by a number of stability tests also made a stable and appropriate formulation that, in comparison to the traditional emulsion, gave phase separation after two days. It was made by sonicating oil and Tween-20 at a ratio of 1:1.2 and 5% garlic essential oils for 35 minutes. It was shown that the garlic EO-based NE was more efficacious than the corresponding emulsion, even after accounting for the stability issue. NE demonstrated LC50 values on *A. oleae* and *T. hassani* of 298.22 and 309.634 µg/mL,

respectively, up to 584.878 and 677.830 µg/mL of the emulsion.

Badawy et al. 2017 [44] developed four distinct nanoemulsions (NEs) using essential oils (EOs) from *Callistemon viminalis* G. Don and *Origanum vulgare* L., along with the monoterpenes R-limonene and pulegone. In a greenhouse setting, they looked at the fumigant and contact toxicity of 10% concentrated NEs on *T. urticae* as well as its effects on bean plants. The monoterpene-based NEs revealed to be more toxic against the target organism and to cause an activity outbreak more quickly, despite the fact that the entire formulations shown great efficacy. Furthermore, compared to contact toxicity, fumigant toxicity was more noticeable. Supplying this compound in vapour phase affects respiratory system of target organism.

5. Nano emulsions as insect and tick repellents

More than a million people die each year from diseases carried by hematophagous insects, including dengue, malaria, zika, and yellow fever [58]. To cure or prevent such diseases, new targeted medications or vaccines are required; however, a reliable strategy for controlling them involves effective vector control methods, which have demonstrated epidemiological impact. Chemical compounds known as repellents can stop an arthropod from settling on the skin and biting [59]. They work topically by creating a vapour layer that keeps an arthropod species from coming into touch with human skin by giving it an unpleasant stench. It is preferable for these molecules to stay in the stratum corneum rather than enter the bloodstream [60].

Some essential characteristics should be included in the perfect arthropod repellent: (i) wide range of action; (ii) prolonged action (>8 hours); (iii) no harm to humans or the environment; (iv) little penetration and no skin allergy ; (iv) odorless to humans and intolerable to arthropods [58].

These days, spray solutions and lotions are the most common types of traditional repellents available. The first ones are emulsions with low stability, while the second ones require a high concentration of alcohol to solubilize the active components. On the contrary, NEs are able to overcome these issues. NE composition is

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physiologically acceptable, they are quite stable, and they have a low viscosity to make them easy to apply to the skin and plant surface.

Nanoemulsion based on EOs of hairy basil (*Ocimum americanum* L.), citronella (*Cymbopogon citratus* (DC. (Stapf)), and vetiver (*Vetiveria zizanioides* (L.) Nash) were developed and evaluated their *in-vitro* physicochemical characteristics. Their physicochemical characteristics, *in vitro* release, *in vivo* effectiveness against *Ae. aegypti*, and toxicity against normal human foreskin fibroblast (NHF) cells were all assessed. The formulations were compared both before and after high-pressure homogenization. Smaller oily droplets, measuring between 150 and 160 nm, were produced with this high-energy procedure. After two months, they showed improved stability, as indicated by zeta potential values. Furthermore, it was found that the oily droplets' tiny size was crucial to the formulation's effectiveness. In actuality, NEs had prolonged repellent action and a superior discharge rate, as determined by a dispersal mechanism. The scientists hypothesized those formulations with lesser sizes able to establish a full film on the skin in order to prolong the activity. The combo of 10% vetiver EO, 5% hairy basil, and 5% citronella found to be the most beneficial in terms of size, stability, and efficacy (4.7 hours of protection).

The synthesis and characterisation of neem oil NE were examined by Choupanian et al., [42], who also assessed the inclusion of two surfactants (alkylpolyglucoside and polysorbate) to enhance the stability of the NE. *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst.), two significant pests of stored goods, were used to test the biological activity of neem oil NE. All of the NEs displayed droplet sizes between 200 and 600 nm, and the formulation with the highest percentage of non-ionic surfactants had smaller droplets than the formulations with the same surfactant composition but lower concentration. The addition of non-ionic surfactants increased the viscosity of the nanoemulsion (NE). After 48 hours of treatment, all pests exposed to the NE showed 100% mortality, except for the 1% formulation (507 nm droplet size), which achieved 74% mortality in *S. oryzae* and 85% in *T. castaneum*. The reduced efficacy of the 1% NE was attributed to its larger droplet size. However, when compared to free neem oil and

Neemix®, all NEs shown stronger harmful effects against both pests.

Hashem et al., 2018 [62] evaluated the insecticidal effects of a nanoemulsion containing *Pimpinella anisum* L. After 72 hours of exposure, the LC50 value was 9.84%. Twelve hours later, the adult mortality rate was 81.33 ± 0.08%, and if the offspring were exposed to 10% nanoemulsion, the mortality rate decreased by 70.85%. Among other parts of the insect's body, the nanoemulsion affixed itself to the head, thorax, abdomen, elytra, mouth, and legs. Furthermore, the insects' midgut cells underwent a unique type of modification brought on by the NE. Furthermore, the insects' midgut cells underwent a unique type of modification brought on by the NE.

According to Nuchuchua et al., [63] formulated NE incorporating vetiver, citronella oil and hairy basil oil by high pressure homogenization and montanov 82. Stable NE with essential oil repellent was prepared against *Aedes aegypti*. NE against mosquito was analyzed by different parameters such as stability, droplet size, *in vivo* efficient studies. The result showed that size of formulation was about 153.2 nm, high stability and -51.3 mV negative zeta potential. The active ingredient in citronella oil that repels *Aedes aegypti*, limonene, demonstrated prolonged release when formulated in a mosquito repellent mixture. According to *in vivo* efficacy tests, formulation 7, which is an oil combination, had an action time duration of 4.7 hours against *Aedes aegypti*.

Pant et al., [64] prepared nanoemulsions from eucalyptus oil and assessed how adding *Pongamia glabra* and *Jatropha curcas* aqueous filtrate to them increased their insecticidal effectiveness. The estimation of insecticidal activity was treated against *Tribolium castaneum*, a significant pest of grains. 10% eucalyptus oil concentration in each of the four formulations was the same; the only factor that different was the content of karanja and jatropha in the aqueous filtrate (0%, 20%, 49%, and 60%). All formulations tested showed a similar percentage of *T. castaneum* insecticidal activity.

6. Nanoemulsion as herbicides

An important development in sustainable farming methods is the use of nanoemulsions as herbicides, which offer a practical way to suppress undesirable plant growth with the least possible negative effects on the environment. Recent research has shown that nanoemulsions have strong herbicidal effects, especially when made with essential oils like citronella oil. One study, for example, focused on the creation of nanoemulsions using citronella essential oil, which had a notable dose-dependent inhibitory impact on the germination and seedling development of the common weed *Echinochloa crus-galli*. Because of their small droplet sizes (usually between 20 and 200 nm), which increase the active components' penetration into plant tissues and bioavailability, nanoemulsions have several advantages [65-67]. Compared to traditional herbicides, this improved efficacy enables lower application rates, which lowers the environmental chemical burden overall. Furthermore, the growing need for environmentally responsible pest control methods is in line with the utilization of natural chemicals in nanoemulsion formulations. Furthermore, nanoemulsions are a good substitute for conventional herbicides due to their unique properties, which prolong herbicidal efficacy. All things considered, using nanoemulsion technology in herbicide formulation not only increases efficacy but also encourages sustainable farming methods by lowering dependency on artificial chemicals [68-70].

Herbicides are applied to unwanted plants (weeds) to control them. For instance, monocotyledonous and dicotyledonous weed species can be controlled with the non-selective herbicide glyphosate [N-(phosphonomethyl) glycine], which is applied on foliage [71]. By stopping the shikimate pathway and deactivating 5-enolpyruvyl shikimate-3-phosphate synthase to slow down weed growth, glyphosate plays a significant role in blocking the formation of phenylalanine, tryptophan, and tyrosine (aromatic amino acids) [72]. Since hydrated herbicides have a poor ability to absorb, translocate, and permeate the waxy layer of leaves, nanoemulsion-based herbicides have the potential to enhance the bioavailability of glyphosate [73]. They investigated the efficient management of *Eleusine indica* using a green nanoemulsion formulation containing water-soluble glyphosate. *Chenopodium album*

and *Amaranthus retroflexus* were successfully destroyed by a natural herbicide nanoemulsion. The primary chemical components of *S. hortensis* are γ -terpinene and carvacrol, which have herbicidal activity because of their phytotoxic impact.

Hazrati et al., [74] assessed the herbicidal activity of O/W NE containing *Satureja hortensis* essential oil (EO) against the common weeds *Chenopodium album* and *Amaranthus retroflexus*. Droplet size measurements for the NE were 92.7 ± 2.6 nm and PDI 0.29 ± 0.01 , respectively. Following 30 days of storage, the PDI decreased and the mean diameter increased. In a lab setting, the percentage of germination exhibited a dose-dependent response, with the concentration of 800 μ l/l nanoemulsion exhibiting the strongest germination inhibition against *Chenopodium album* and *Amaranthus retroflexus*. Compared to shoot elongation, root elongation was significantly impacted in this experiment. Additionally, a dose-dependent decline in plant growth was seen in greenhouse experiments. Furthermore, five days post-treatment, there was an estimated rise in relative electrolyte leakage and decrease in chlorophyll content, which might be explained by rupture of the cell membrane and increased permeability. This NE's inclusion of carvacrol, a phenolic monoterpene with potent phytotoxic properties, gave it herbicidal action against weeds.

Water-soluble herbicide nanoformulation containing isopropylamine glyphosate utilized as herbicide agent against three weeds *Asystasia gangetica*, *Diodia ocimifolia*, and *Paspalum conjugatum*. Comparing the glyphosate NEs to a commercial formulation (Roundup®), the authors observed that all species displayed reduced spray deposition of the NEs. Nevertheless, over a 14-day treatment period, the injury rates of the weeds treated with NE resembled those of the plants treated with commercial formulation [75]. Potentiation of the biological activity when glyphosate was manufactured as NE may be the reason for the comparable herbicidal properties of both the commercial product and nanoemulsion, despite the fact that nanoemulsion deposition has decreased.

7. Nanoemulsion as nematocides

Worldwide, a variety of economically significant crops are harmed by plant parasitic

nematodes. Nematodes are extremely hard to control; although pesticides are an effective instrument in the fight against them, they have a number of detrimental effects on the environment and living things. It is crucial to provide an alternative approach to pest management that is both environmentally safe and just as effective as synthetic pesticides. The fastest and most effective method for creating nanoemulsion with tiny size dispersion and nano droplet sizes is known as the greatest energy approach [76]. Numerous studies have shown that the main ingredient in essential oils, monoterpenes, has strong antibacterial properties in nanoemulsions [77].

A few monoterpene nanoemulsions, including cinnamaldehyde, citral, geraniol, (R)-carvone, and pulegone, have been shown to have nematocidal action, which significantly decreased egg hatching and increased juvenile mortality in root-knot nematode, *Meloidogyne javanica* [78]. The population of *M. javanica*, egg masses, and root galls are all severely inhibited by the nematocidal activity of the nanoemulsion. It is unknown how essential oils and monoterpenes affect nematodes. Nonetheless, it has been discovered that a variety of volatile oils cause *Drosophila melanogaster* to develop cancer by deleting GABA receptors and activating octopaminergic receptors [79, 80]. When tomato plants are inoculated with *M. javanica*, the action of anti-oxidant enzymes such as peroxidase and polyphenol oxidase is improved by the use of monoterpenes nanoemulsion. Consequently, resistance against phytonematodes is provided by the monoterpenes nanoemulsion. Potentially just as successful as a synthetic nematode that had been destroyed by carbofuran, the worm population's growth was reduced by the nanoemulsion derived from citronella oil [81].

8. Nanoemulsion as fungicides

Small size of fungicide based nanoemulsions enables them to pass through the fungal cell membrane. By creating a nanoemulsion, fungicides become more soluble in water, which facilitates their integration with the phospholipid bilayer of microorganisms and their ability to reach the surface of their cell membranes. This Cell death is facilitated by permeation, which also speeds up cell disintegration. Tebuconazole nanoemulsion has been created as a possible fungicide that is less

harmful than commercial preparations of the same name. The same is true for mancozeb-containing nanoemulsions, which have demonstrated increased efficacy in their antifungal action against *Glomerella cingulate*.

The usage of Tebuconazole (TBZ) as a fungicide in nanoemulsion formulation for agricultural applications was determined by Diaz-Blancas et al., [82]. The average leaching potency of TBZ into groundwater with an incorporation of constant Koc (for organic carbon) ranging from 803 to 1251 ml/g, it is a persistent insecticide. Because of its systemic action mechanism, TBZ can be ingested by plant roots and leaves, which stops ergosterol from forming. This type of obstruction prevented pathogens from synthesising on the cell wall and decreased germ tube germination. Abd-Elsalam et al., [83] used water as a continuous aqueous phase and Tween 20, a non-ionic detergent, to characterise and create ethylene glycol nanoemulsion antifungal activity on cotton. According to an in vitro antifungal study, eugenol nanoemulsion prevents *Fusarium oxysporum f. sp. vasinfectum*—the pathogen that causes Fusarium droop in valuable yield crops—from growing. Eugenol has the ability to deactivate significant enzymes that affect the cell membrane or impede the action of nucleic acids [84]. Eugenol also prevents the production of ergosterol (De-Oliveira Pereira et al., 2013). Eugenol nanoemulsion prevents the pathogen's sporulation, radial growth, and coloration [83]. The deformation of fungal mycelia is a part of its mode of action. It acts as an antibiotic against a variety of phytopathogens, toxic fungi, and food-borne microorganisms. A non-ionic nanoemulsion based on lemongrass and clove oil inhibited the fungus that causes vascular wilt's growth and development, *Fusarium oxysporum f. sp. Lycopersici* [85]. According to research by Da Silva et al., [86] ethylene nanoemulsion may be a safe formulation for use in agriculture that won't harm DNA or result in the creation of reactive oxygen species or reduce cell viability. They did not exhibit ecotoxicity towards *Folsomia candida*, either.

The antifungal activity of nanoemulsions against *Fusarium oxysporum f.sp. lycopersici* (FOL) was assessed by Sharma et al., 2018 [85] utilizing a detergent emulsifier and a blend of two essential oils: lemongrass oil and clove oil. 80% water, 10% detergent (Tween 20: CoE-40 in a 7:3 ratio), 5% propylene glycol, and 5% a

1:1 blend of lemongrass and clove oil made up the optimal formulation. The final nanoemulsion exhibited a polydispersity index (PDI) of 0.207 ± 0.02 ; a droplet size of 76.73 ± 4.8 nm; and a viscosity of 26.9 ± 1.9 cP. The nanoemulsion showed significantly better fungicidal activity, with a minimum inhibitory concentration (MIC) of 4000 mg/L, which was 48.5% more effective at suppressing mycelial development than the free oil combination, which had a MIC of 7000 mg/L. Additionally, at a dosage of 5000 mg/L, the NE had more potent fungicidal effects against FOL than the free oil combination, which needed 9000 mg/L to provide comparable outcomes [86]. This suggests that the nanoemulsion weakened the membrane integrity of FOL.

Ali et al., 2017 [87] used low energy spontaneous emulsification to create NEs with neem and citronella oil. To test the antifungal activity two phytopathogenic fungi, were used of Nes are *Rhizoctonia solani* and *Sclerotium rolfsii*. Each oil produced an optimal primary emulsion with a water:oil:surfactant ratio of 8.50:0.50:1. This initial emulsion was used to construct citronella oil nanoemulsions (NEs) with varied neem oil concentrations (0.5–5%), and vice versa, neem NEs were made with different citronella oil concentrations (0.5–5%). The droplet sizes in the citronella oil NEs with different concentrations of neem oil ranged from 8.12 ± 2.80 nm to 12.04 ± 3.74 nm, whereas the droplet sizes in the neem NEs with different amounts of cymbopogon oil ranged from 11.23 ± 3.86 nm to 17.80 ± 4.52 nm. Diverse percentages of citronella oil produced droplet sizes ranging from 11.23 ± 3.86 nm to 17.80 ± 4.52 nm, whereas diverse amounts of citronella oil produced particle sizes ranging from 8.12 ± 2.80 nm to 12.04 ± 3.74 nm. Using the poisoned food approach, the antifungal activity of the different NEs against *Sclerotium rolfsii* and *Rhizoctonia solani* was assessed. The best antifungal action against both fungi was demonstrated by the citronella NE with the highest percentage of neem oil and the neem NE with the highest percentage of citronella oil. Neem NE and citronella NE were shown to have respective estimated LC₅₀ values of 13.67 mg/L and 25.64 mg/L against *R. solani*, and 14.71 mg/L and 20.88 mg/L against *S. rolfsii*.

9. Nanoemulsion in Antiparasitic Drug

Nanoemulsions have the ability to enhance the bioavailability and effectiveness of active

ingredients, their use in antiparasitic medication administration has drawn a lot of interest. Because of their small droplet size (usually between 10 and 100 nm), nanoemulsions offer a special platform for enhancing the stability and solubility of medications that are not very soluble in water [88, 89]. Neem oil nanoemulsions, for example, have been demonstrated to be efficient biopesticides by exhibiting strong larvicidal and ovicidal effects against a variety of mosquito vectors. Non-ionic surfactants, which stabilize the emulsion and improve its bioactive qualities, have been used in recent studies to produce neem oil nanoemulsions. These compositions' antifungal and antiparasitic properties are further enhanced by the use of essential oils like citronella and clove oil. These nanoemulsions have demonstrated encouraging outcomes against pathogens such as *Sclerotium rolfsii* and *Fusarium oxysporum*, suggesting that they could be useful therapeutic agents in both medical and agricultural settings. Additionally, better droplet size and stability—both of which are essential for enhancing bioavailability and therapeutic effects—have resulted from the formulation parameters being optimized using response surface approach [90, 91]. All things considered, the development of antiparasitic medications using nanoemulsions is a flexible and creative method that maximizes effectiveness while reducing environmental impact.

NEs were tested as a target vehicle for andiroba and copaiba oils (nanoandiroba and nanocopa with a standard droplet size of 88.1 and 76.1 nm, respectively) using *Leishmania infantum* (LI) and *Leishmania amazonensis* (LA). The result of scanning electron microscopy showed parasite shape change to oval shape after VL, CL after 1 hour nanoemulsion administration [92].

A *Lavanudula* species nanoemulsionated EO was investigated for its antiparasitic properties against *Leishmania major*, the species that causes *L. amazonensis*. Specifically, the parasite was significantly killed by NE combined with EO of *Rosmarinus officinalis* L. and *L. angustifolia* Mill., where the main constituents were 1,8-cineol and linalool. The antiparasitic effects of the EOs of *Lavanudula angustifolia* and *Rosmarinus officinalis* were significantly greater in the NE than in the EO nanoemulsion of *Rosmarinus officinalis* [93].

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Zinc phthalocyanine nanoemulsion in photodynamic therapy (PDT), was potent against *Leishmania* species and had a number of benefits over other topical treatments including amphotericin B and paromomycin. Liposoluble medications, such as PS, are effectively dissolved in water by NEs. In order to create a dermal

delivery system for PDT, polymeric surfactant (Pluronic® F127), a zinc phthalocyanine (PS) oil-in-water NE, essential clove oil, and were utilized against *L. amazonensis* and *L. infantum* [97-99]. Table 2 represents nanoemulsion with different composition for agricultural applications.

Table 2 – Nanoemulsion formulation and its composition for various agricultural applications

Nanoemulsion composition	Concentration	Application in agriculture	Reference
Carvone, citral, pulegone oils, cinnamaldehyde	(10 v/v%)	Antibacterial activity against <i>Ralstonia solanacearum</i> and <i>Pectobacterium carotovorum</i>	[56]
Clove oil	(1 w/v%)	Antifungal activity against <i>Glomerella cingulata</i>	[85]
Eucalyptus oil	(6-10 w/w%)	Insecticidal activity against <i>Sitophilus oryzae</i> and <i>Tribolium castaneum</i>	[92]
Neem oil	(0.5-3 w/v%)	Antifungal activity against <i>Aspergillus flavus</i>	[93]
Thyme essential oil	(10 v/v%)	Antifungal activity against <i>Sclerotinia sclerotiorum</i>	[94]
Sweet flag oil	(6 v/v%)	Insecticidal activity against pulse beetle	[95]
Eugenol oil	(3.3 v/v%)	Antifungal activity against <i>Glomerella cingulata</i>	[96]

10. Current Trends in Nanoemulsion Applications in Agriculture

The revolutionary significance that nanoemulsions play in improving the sustainability and effectiveness of agrochemicals is highlighted by current trends in their use in agriculture. Significant advancement is the nanoencapsulation of fertilizers and insecticides, which reduces the necessary dosages by 20-40% as compared to traditional formulations and enhances the solubility and bioavailability of the active components [100]. In addition to reducing environmental runoff, this precise delivery method facilitates adherence to strict ecological regulations. Targeted nutrient delivery is made possible by the combination of nanoemulsions and precision agriculture technology, which maximizes crop resilience

and uptake rates in areas susceptible to drought [101-103]. Current developments center on climate-smart formulations that include micronutrients like iron oxides and zinc, which reduce abiotic stress and boost yields by 15-30% in field tests.

Nano-fertilizers are expected to increase at a 13.7% CAGR from 2024 to 2030, according to market studies, thanks to government incentives that support environmentally friendly practices [104]. At the same time, biodegradable nanoemulsion systems are becoming more popular. These systems use emulsifiers produced from plants to distribute agrochemicals while preserving the health of the soil microbiota. Essential oil-based antimicrobial nanoemulsions that inhibit phytopathogens like *Pseudomonas syringae* without increasing the

danger of antibiotic resistance are among the emerging uses [105]. AI-optimized emulsion systems are also being used more frequently in this industry to modify nutrient release profiles in real time using data from crop sensors. Strategic industry partnerships are creating low-energy emulsification processes to increase commercial viability, despite ongoing issues with large-scale manufacturing costs that are 15%–20% higher than classic formulations [106]. In order to guarantee safety, regulatory agencies are simultaneously developing nano-specific standards and promoting creativity in formulations that are compatible with organic materials.

11. Safety measures of Nanoemulsion in Agriculture

Nanoemulsion uses in agriculture have advanced recently, necessitating integrated safety measures that combine material innovation and regulatory control. The UK's Health and Safety Executive imposes droplet size standardization (20–200 nm) and AI-driven release kinetics to reduce overdosing, while the EU's REACH (2024) requires lifetime evaluations for nano-agrochemicals. The US EPA mandates risk assessments that are particular to nanotechnology and concentrate on the effects on non-target organisms and bioaccumulation. When compared to their synthetic counterparts, GRAS-certified emulsifiers such as methylcellulose and plant-derived surfactants reduce phytotoxicity by 30 to 45%. Groundwater contamination is reduced by 92% and soil microbiome compatibility is improved by biodegradable matrix (such as lignin and

chitosan). Targeted release made possible by encapsulation technology reduces pesticide residues in crops by 58% while preserving effectiveness against diseases such as *Colletotrichum gloeosporioides* [107]. Long-term stability testing and rheological profiling guarantee formulation integrity even in the face of temperature variations (4–40°C).

Ecological concerns are reduced by required buffer zones (15–30 m) and nanoparticle tracking systems. Essential oil-based nanoemulsions such as neem and cinnamon increase crop germination rates by 18–33% while inhibiting fungal development without increasing the danger of antibiotic resistance. To lessen inhalation exposure during application, closed-system production and HEPA-filtered personal protective equipment (PPE) are now commonplace. Harmonizing international ecotoxicity standards and alleviating public concerns through transparent labeling remain challenging tasks [108 -112]. Blockchain-based supply chain monitoring and CRISPR-edited bioindicators for contamination identification are examples of emerging solutions. The use of nanosensors and computerized controls significantly contributes to precision farming; nanomaterials can be used to promote plant stress tolerance and soil enhancement; controlled released nanofertilizers improve crop growth, yield, and productivity; nano-based target delivery approach (gene transfer) is used for crop improvement; and nanopesticides can be used for effective crop protection. For more information, readers are directed to the text [113]. The applications of nanoemulsion in modern agriculture practices were depicted in Figure 3.

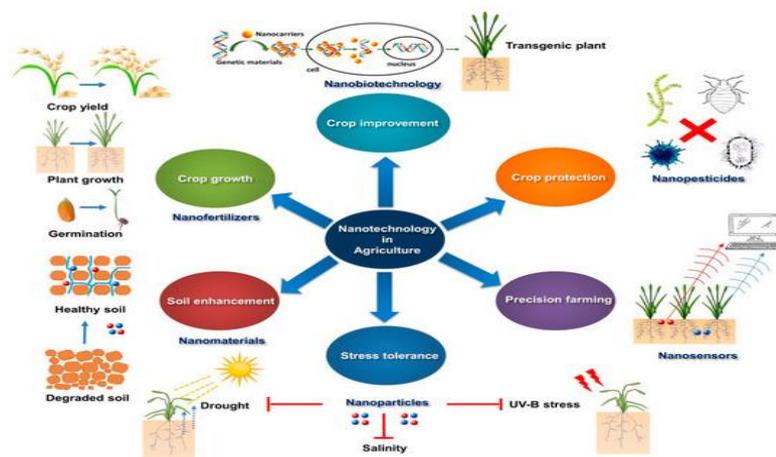


Figure 3: Applications of nanoemulsion in modern agriculture practices [113] (open access)

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CONCLUSION

In agriculture, nanoemulsions have become a game-changing technology that provides creative answers for crop protection, nutrition delivery, and environmental sustainability. The solubility, stability, and bioavailability of agrochemicals are improved by these nanoscale emulsions, allowing for accurate and effective distribution to specific locations. Nanoemulsions greatly reduce environmental contamination and increase the efficacy of pesticides, herbicides, and fungicides by minimizing the loss of active chemicals through runoff, leaching, and volatilization. Furthermore, by lowering dependency on artificial chemicals, bio-based nanoemulsions made from natural substances complement environmentally beneficial farming methods. By guaranteeing sustained action and lowering the frequency of administrations, the use of nanoemulsions also facilitates regulated release mechanisms. They help improve fertilizer absorption in nitrogen management, which boosts crop output and growth. However, obstacles to broad adoption still exist, including issues with cost-effectiveness, large-scale production, and regulatory compliance. While investigating the integration of nanoemulsions with precision farming instruments such as nanobiosensors for real-time monitoring, future research should concentrate on overcoming these constraints. With further development, nanoemulsions have the potential to completely transform contemporary agriculture by enhancing sustainability and efficiency while tackling the problems of global food security. Adoption of these could be a big step toward more resilient and environmentally friendly agriculture systems. In summary, the use of nanoemulsions in agriculture offers a number of benefits over traditional pesticide formulations and represents a revolutionary approach to weed and insect control.

Conflict of interest

All the authors declare that they have no conflicts of interest and approved the final draft of manuscript for publication.

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