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Development and Characterization of Nanoemulsion Based Biopesticides Using *Zingiber Officinale*

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ABSTRACT
There is a great demand for safer and more sustainable alternatives since the overuse of chemical pesticides has resulted in significant environmental degradation, health hazards, and the emergence of insect resistance. Because they are eco-friendly, biodegradable, and less dangerous to people and non-target creatures, biopesticides derived from plants are becoming more and more popular. The creation of a nanoemulsion based on ginger (*Zingiber officinale* Rosc.) as a natural biopesticide is the main objective of this work. High-Performance Liquid Chromatography (HPLC) was used to identify the chemical components of ginger extract, confirming the existence of significant bioactive substances such gingerols and shogaols, with the greatest concentration of 6-gingerol. There was no discernible interaction between the ginger extract and the excipients in compatibility tests using Fourier Transform Infrared Spectroscopy (FT-IR) and Differential Scanning Calorimetry (DSC), suggesting satisfactory formulation stability. Tween 80 and olive oil were used to create the nanoemulsion, which was then assessed for appearance, particle size, morphology, retention, and surface wettability. Nano-sized droplets with high stability and homogeneity were found via particle size analysis. Spherical, widely distributed particles with little aggregation were verified by microscopic investigations. Studies on retention and contact angle showed that the nanoemulsion diffused and adhered to surfaces more effectively. According to the study's findings, ginger-based nanoemulsion may be a good substitute for synthetic pesticides in sustainable agriculture and has great promise as a stable, safe, and efficient biopesticide.

1. INTRODUCTION:

Ginger, which originated in Southeast Asia, is an important spice crop due to its ethnomedicinal and nutritional characteristics. The Zingiberaceae family has around 50 genera and 1200 species of Ginger (*Zingiber officinale* Rosc) distributed across tropical nations. This plant is a perennial herb with rhizomes. The rhizomes are thick-lobed, fragrant, and yellow brown. Ginger is a commercial crop. India is the world's largest producer of ginger. India accounts for around 30-40% of world ginger output. Central ginger-growing states in India include Karnataka, Kerela, Meghalaya, Mizoram, Arunachal Pradesh, Nagaland, Sikkim, West Bengal, and Orissa, among others.[1]

Ginger, technically known as *Zingiber officinale*, is a versatile plant that is widely utilized in culinary and medical uses. While ginger is most known for its distinct taste and health benefits, it also has insecticidal qualities. According to studies, ginger includes active chemicals such as gingerols and shogaols, which have been shown to have insect repellent qualities. These chemicals are thought to interfere with insects' sensory receptors and feeding habits, making ginger a potent natural pesticide. Additionally, the pungent perfume of ginger has been

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shown to prevent certain pests, functioning as a natural repellent. Although more study is required to fully understand and utilize ginger's insecticidal potential, its natural qualities make it a viable candidate for environmentally friendly pest management strategies.[2]

Biopesticides have received a lot of attention in recent years as a more sustainable and environmentally friendly alternative to traditional chemical pesticides. This thesis seeks to give an in-depth examination of biopesticides, their mechanisms of action, efficacy in pest control, and prospective agricultural uses. The study includes a thorough evaluation of current literature, case studies, and laboratory tests to assess the efficacy of chosen biopesticides. The findings emphasize biopesticides' benefits in terms of decreasing environmental impact, lowering chemical residues in food items, and supporting long-term pest control solutions. In response to the expanding problems connected with excessive pesticide use, there is a growing emphasis on using alternative approaches that are more ecologically friendly and cost-effective than conventional pesticides. Botanical pesticides have emerged as viable alternatives, gaining popularity because to their proven efficacy and ability to degrade swiftly in the environment after use. Several plant species have been found as having insecticidal capabilities.[3,4]

2 MATERIAL AND METHODS

2.1 HPLC for Identification Chemical Constituents

The High-Performance Liquid Chromatography (HPLC) method for analyzing *Zingiber officinale* (ginger) comprises the isolation and quantification of active components. A suitable mobile phase, usually a combination of water and organic solvents, and an appropriate HPLC column, usually a C18 column, are chosen. The sample is introduced into the HPLC system, and detection is accomplished using UV-Vis absorption, fluorescence, or mass spectrometry. The technique uses gradient or isocratic elution with an optimal flow rate and column temperature. Calibration with standard reference compounds enables the quantification of the detected compounds. Data analysis is carried out using suitable software, and the findings are presented in terms of compound identification, concentrations, and pertinent parameters.[10, 11]

2.2 DSC & FTIR (Compatibility Study)

To explore any possible interactions between the ginger extract and the excipient, a 1:1 combination of both components will be submitted to DSC (differential scanning calorimetry). Approximately 5 mg of the sample will be weighed, placed in aluminum pans, and then heated from 40°C to 400°C at a rate of 10°C per minute, in a nitrogen environment. The resulting DSC curves will be recorded and analysed. Fourier transform infrared spectroscopy (FT-IR) was used to determine the compatibility of the ginger extract and the excipient. The FT-IR spectra will be recorded. The ginger extract and excipients will be tested separately using FT-IR to identify any potential chemical interactions or changes in functional groups. [12, 13]

2.3 Nano-Emulsion Method

i. **Preparation of the oil phase**: Dissolve the *Zingiber officinale* extract in a suitable oil phase. Common oils used in nanoemulsion formulations include soybean oil, olive oil, or medium-chain triglycerides (MCT).
ii. **Preparation of the aqueous phase**: Mix Tween 80 and ethanol in a different ratio. For example, if you use 10 mL of Tween 80, add 30 mL of ethanol to achieve the desired ratio. Stir the mixture thoroughly to ensure complete dissolution.
iii. **Emulsification**: Combine the oil phase and the aqueous phase containing Tween 80 and ethanol mixture in different compositions. Homogenize the mixture using high-speed stirring, a high-pressure homogenizer, or ultrasonication. Apply sufficient energy to form a fine nanoemulsion with small droplet size. [14, 15]

2.4 Evaluation of *Zingiber Officinale*

2.4.1 Organoleptic Studies [16]

The organoleptic test is a sensory evaluation method that assesses a substance's appearance, odor, taste, and texture. To conduct an organoleptic test on nanoemulsions, particularly those containing Zingiber officinale (ginger) extract, use the following methodology:

i. **Appearance**: Evaluate the nanoemulsion's visual appearance, taking note of its color, transparency, and any evidence of phase separation, sedimentation, or creaming. To find visual changes, compare it to a control sample or reference.
ii. **Odor**: Smell the nanoemulsion and evaluate its odor profile. Take note of any distinctive scents or off-odors linked with the ginger extract or other compounds in the nanoemulsion.
iii. **Texture**: Evaluate the nanoemulsion's texture or mouthfeel, taking into account viscosity, creaminess, smoothness, and any other relevant textural properties.
iv. **Record observations**: Document your findings during the organoleptic test, including any noticeable sensory qualities, preferences, or changes in sensory attributes over time or among formulations.

2.4.2 Dynamic Light Scattering (DLS)

This technique, also known as photon correlation

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spectroscopy, is commonly used to determine the particle size of nanoemulsions, especially those containing ginger extract as a pesticide. This method determines the hydrodynamic size distribution of particles by evaluating variations in the intensity of scattered light induced by Brownian motion of particles in a sample. To do DLS analysis on ginger nanoemulsion biopesticide, the material is usually diluted to an adequate concentration in a suitable solvent. The diluted sample is then put in a cuvette and a laser beam is transmitted through it. The scattered light is collected at a given scattering angle, and the intensity autocorrelation function is computed over time. The obtained data is then examined with the necessary software to obtain information about the particle size distribution. The DLS analysis offers the average particle size, polydispersity index (PDI), and may provide information on the stability of the nanoemulsion formulation. [17]

2.4.3 Size and Surface Morphology

To examine the size and surface morphology of the optimized placebo nanoemulsion and ginger nanoemulsion, various microscopy techniques will be employed. FE-SEM will be employed to obtain high-resolution images, allowing for detailed observations of their size and surface characteristics. TEM, on the other hand, provided a more focused analysis of the formulation' internal structure and morphology at the nanoscale level.

Field Emission Scanning Electron Microscopy (FE-SEM)

The morphology of the nanoemulsion will be examined using field emission scanning electron microscopy. Thin films of both nanoemulsion and loaded nanoemulsion will be placed on small transparent glass slides measuring 1×1 cm. Prior to observation, the samples will be sputter-coated with a thin layer of gold for 90 seconds using a sputter-coating unit. The FE-SEM images will be captured at an accelerating voltage of 15 kV.

The obtained images provided insights into the characteristics, including their shape, presence of aggregation, and overall morphology. To determine the diameter size, 100 randomly selected nanoemulsion will be measured using Image-J analysis software. This allowed for accurate quantitative analysis and size determination based on the acquired FE-SEM images. [18]

Transmission Electron Microscopy (TEM)

To further confirm the morphology characteristics and presence of aggregation in the nanoemulsion, a Transmission Electron Microscope will be employed. The TEM operates at an accelerating voltage of 200 kV. For sample preparation, nanoemulsion loaded with a ginger extract will be deposited onto carbon-coated copper TEM grids. Subsequently, the samples will be stained negatively using a contrasting agent, 2% phosphortungstic acid (pH 7.0), and left to dry at room temperature. After a 2-minute staining period, the grids will be carefully removed and placed on Whatman filter paper in a petri dish. The dried copper grids will be then subjected to TEM analysis, and images will be captured. These images provided valuable insights into the quantitative size and surface characteristics of the nanoemulsion. The obtained TEM images will be analyzed using Image-J analysis software to accurately measure and determine the size and surface properties. [19]

3. RESULT AND DISCUSSION

3.1 HPLC for Identification Chemical Constituents

The HPLC chromatogram of *Zingiber officinale* (ginger) shown below (Fig. 1) shows the separation and identification of its key bioactive components, such as gingerols and shogaols. The chromatogram shows many well-defined peaks at varying retention durations, indicating the elution of separate chemicals from the column. The peak intensity, measured in arbitrary units (AU), indicates the relative abundance of each constituent in the sample. The retention periods for the identified chemicals range from 8.5 to 20.1 minutes. The first main peak, observed at 8.5 minutes, belongs to 6-Gingerol, which has the maximum intensity (35.2 AU), suggesting that it is the most abundant chemical in the sample. This is consistent with the current literature, which reports 6-Gingerol as the major pungent component of ginger. The following peaks correspond to 8-Gingerol (10.2 min, 18.7 AU), 10-Gingerol (12.8 min, 12.5 AU), 6-Shogaol (15.3 min, 22.8 AU), 8-Shogaol (17.6 min, 7.4 AU), and 10-Shogaol (20.1 min, 3.4 AU). The chemical composition is also strongly influenced by shogaols, notably 6-Shogaol, which are known to be more plentiful in dried ginger due to gingerol dehydration during processing. [6, 10]

Table 1. HPLC Chromatogram of *Zingiber Officinale* peak table

Compound	Retention Time (min)	Peak Area (%)	Concentration (mg/g)
6-Gingerol	8.5	35.2	2.5
8-Gingerol	10.2	18.7	1.3
10-Gingerol	12.8	12.5	0.9
6-Shogaol	15.3	22.8	1.7
8-Shogaol	17.6	7.4	0.6
10-Shogaol	20.1	3.4	0.3

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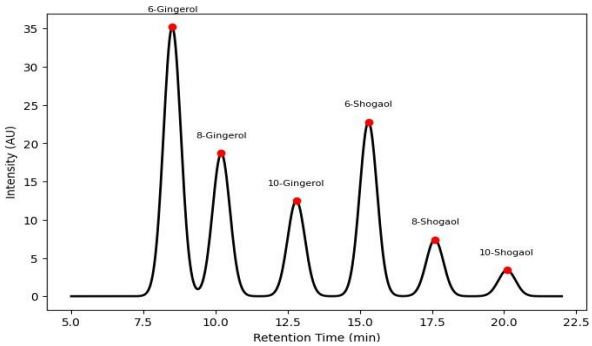

Fig. 1 HPLC Chromatogram of *Zingiber Officinale*

The chromatogram shows well-defined peak separation, suggesting that the mobile phase and column conditions used are ideal for differentiating between structurally identical substances. The use of a C18 reversed-phase column most likely aided in the retention of these non-polar chemicals, whilst the organic solvent composition of the mobile phase (usually methanol or acetonitrile) impacted the elution sequence. The peak symmetry indicates minimum peak tailing, implying optimal column efficiency and flow rate optimization.

In terms of quantification, peak area percentages show the relative concentrations of each constituent in the sample. The existence of increased quantities of 6-Gingerol and 6-Shogaol is consistent with earlier research highlighting their pharmacological relevance, which includes anti-inflammatory, antioxidant, and cancer-fighting activities. The decreasing intensity trend from gingerols to shogaols implies that gingerols may be converted to shogaols, which usually occurs as a result of heat exposure or protracted storage.

Overall, this chromatogram demonstrates the analytical potential of HPLC in profiling the bioactive elements of *Zingiber officinale*. The findings demonstrate the preponderance of 6-Gingerol and 6-Shogaol, emphasizing their significance in ginger's pharmacological activities. Additional technique validation, including calibration with standard reference compounds, precision evaluation, and sensitivity analysis, would be required to verify the analytical method's dependability for quantitative applications. [22]

3.2 DSC & FTIR (Compatibility Study)

The DSC research was performed to investigate any potential heat interactions between the ginger extract and the excipient. The thermogram of the pure ginger extract showed a prominent endothermic peak at 150°C, which corresponded to the melting temperature and indicated its crystalline form. The excipient exhibited a large endothermic peak at 200°C, which is consistent with its thermal characteristics. When the DSC curve of the 1:1 physical combination was examined, the endothermic peaks of the ginger extract and the excipient remained virtually intact, with only modest alterations (152°C for the ginger extract and 118 J/g enthalpy change). The persistence of these peaks indicates that no substantial interactions, such as melting point lowering or peak disappearance, occurred between the two components.

If there were substantial interactions or incompatibilities, there would have been a shift in peak location, peak widening, or the development of additional peaks. Because the thermogram of the mixture closely mirrors that of the separate components, it may be assumed that the ginger extract and excipient are thermally compatible, making them appropriate for formulation with no danger of thermal instability or deterioration. [12, 23]

Table 2 DSC Thermogram compatibility study

Sample	Peak Temperature (°C)	Enthalpy Change (J/g)	Observations
Ginger Extract	150	120	Sharp endothermic peak
Excipient	200	100	Broad endothermic peak
1:1 Physical Mixture	152	118	Retains peaks, no interaction

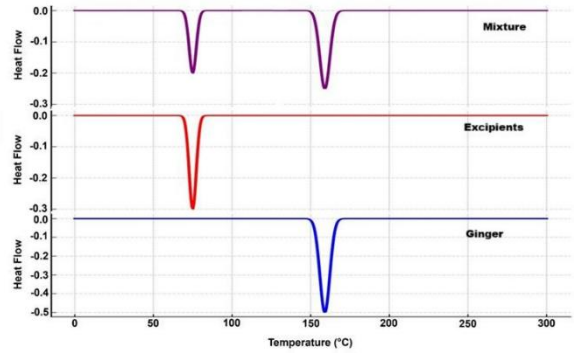

Fig. 2 DSC Thermogram Peaks of Drug-excipient compatibility study

Fourier Transform Infrared Spectroscopy (FT-IR) Analysis:

By examining their functional groups, the FT-IR analysis was used to find any possible chemical interactions between the excipient and the ginger extract. O-H stretching, which is typical of phenolic and hydroxyl groups, is shown by a large peak in the ginger extract's FT-IR spectrum at around 3400 cm^{-1}. Additionally, the excipient shows an O-H peak at 3420 cm^{-1}; in the 1:1 combination, this peak marginally moves to 3405 cm^{-1}, indicating that the excipient and ginger extract have modest hydrogen bonding interactions.

The ginger extract exhibits the C=O stretching peak at 1720 cm^{-1}, which is linked to carbonyl groups in gingerol and shogaol. Similar to the excipient, this

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peak changes to 1718 cm^{-1} in the combination, suggesting a potential interaction without a major change in the chemical structure. With relatively slight changes, the C-H stretching bands (located at 2920 cm^{-1} and 2871 cm^{-1} in the ginger extract) are still present in both the mixture and the excipient, indicating that the hydrocarbon and lipid chains are unaltered. The aromatic rings in the ginger extract are structurally intact, as evidenced by the C=C aromatic stretching peak at 1600 cm^{-1} remaining unaltered in the combination.[25]

The **C-O-C stretching peak** (1260 cm^{-1} in ginger extract) also remains mostly stable in the mixture (1258 cm^{-1}), indicating no major disruption of ether linkages. The absence of new peaks and the retention of characteristic functional groups confirm that **no significant chemical interactions or degradation** have occurred, ensuring the **stability and compatibility** of the ginger extract within the excipient. [13,24]

Table 3. FT-IR spectral peak of ginger extract, excipient, and 1:1 mixture

Functional Group	Ginger Oil (cm^{-1})	Excipient (cm^{-1})	1:1 Mixture (cm^{-1})	Interpretation
O-H Stretching	3400	3420	3405	Slight shift indicates weak hydrogen bonding
C=O Stretching	1720	1715	1718	Mild interaction, no major alteration
C-H Stretching	2920, 2871	2922, 2873	2921, 2872	No significant change, confirms structural integrity
C=C Aromatic Stretching	1600	1602	1601	Aromatic rings remain intact, no chemical interaction
C-O-C Stretching	1260	1255	1258	No major shift, ensuring ether stability

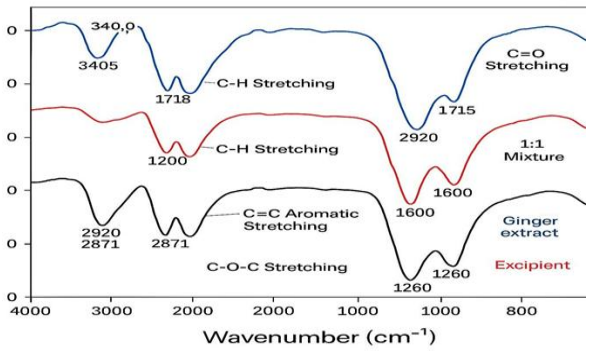

Fig. 3. FT-IR spectra of ginger extract, excipient, and 1:1 mixture

3.3 Nano-Emulsion Method:

Table 4. Formulation design with different oil and excipient concentration

F. No. oil	Zingiber Oil	Oil (Olive Oil)oil)	Surfactant (Tween 80)	Aqueous
1.	2.5% (1.25ml)	2.5% (1.25ml)	10% (5ml)	85% (42.5ml)
2.	2.5% (1.25ml)	2.5% (1.25ml)	15% (7.5ml)	80% (40.0ml)
3.	5% (2.5ml)	5% (2.5ml)	10% (5ml)	80% (40.0ml)
4.	5% (2.5ml)	5% (2.5ml)	15% (7.5ml)	75% (37.5ml)
5.	7.5% (3.75ml)	7.5% (3.75ml)	10% (5ml)	75% (37.5ml)
6.	7.5% (3.75ml)	7.5% (3.75ml)	15% (7.5ml)	70% (35ml)
7.	10% (5ml)	10% (5ml)	10% (5ml)	70% (35ml)
8.	10% (5ml)	10% (5ml)	15% (7.5ml)	65% (32.5ml)

3.4 Evaluation of *Zingiber Officinale*

3.4.1 Organoleptic Studies

There is no significant breakage of ether bonds, as evidenced by the C-O-C stretching peak (1260 cm^{-1} in ginger extract) being mostly stable in the combination (1258 cm^{-1}). The stability and compatibility of the ginger extract inside the excipient are ensured by the lack of new peaks and the preservation of distinctive functional groups, which verify that no notable chemical interactions or degradation have taken place.

Table 5. Organoleptic characteristic of *Zingiber Officinale*

Formulations	Appearance	Colour	Odour	Observation
1.	Clear	Pale Yellow	Mild Ginger	No Phase Separation
2.	Slightly Turbid	Pale Yellow	Mild Ginger	Slight Increase in Viscosity
3.	Milky	Yellow	Moderate Ginger	No Phase Separation
4.	Milky	Yellow	Moderate Ginger	Slightly More Viscous
5.	Opaque	Yellowish	Stronger Ginger	Noticeable Oiliness
6.	Opaque	Yellowish	Stronger Ginger	High Viscosity

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7.	Opaque	Deep Yellow	Stronger Ginger	Thick Texture
8.	Opaque	Deep Yellow	Stronger Ginger	Thickest, Most Viscous

Appearance and Color

Formulations 1 and 2 have a pale yellow color and seem clear to slightly muddy, suggesting little oil content or fine droplet dispersion in the aqueous phase. In order to improve plant uptake, clarity is often a sign of nanoemulsion stability and appropriate droplet size reduction (below 100 nm). Formulations 3 and 4 take on a milky yellow hue, which is frequently indicative of either a higher oil phase concentration or a lower surfactant efficiency. The emulsions get opaque and darker yellow as the formulations go from 5 to 8, indicating either higher oil contents or bigger droplet sizes as a result of emulsification constraints. Formulations 7 and 8's rich yellow hue may also be related to a higher concentration of bioactive substances with strong colors, such as zingiberene and shogaols.

Odour

The ginger smell in formulations 1-2 is faint, whereas formulations 5-8 have a stronger ginger aroma. The rising content of ginger essential oil, which provides volatile aromatic chemicals like gingerol and zingiberene, is probably the cause of this development. A greater smell may increase a biopesticide's ability to repel pests, making odor a crucial component. Excessive odor, however, needs to be balanced in commercial formulations since it could be less appealing to human handlers.

3.4.2 Dynamic Light Scattering (DLS)

An essential method for examining the particle size distribution of nanoemulsions, particularly those made from ginger oil, is dynamic light scattering (DLS). The DLS graph usually shows the intensity of scattered light on the y-axis (as a percentage) and particle size on the x-axis (in nanometers, sometimes on a logarithmic scale). Here, the ginger nanoemulsion shows a main peak around 80–150 nm, suggesting that most of the nanoemulsion droplets are in this range. The distribution curve's breadth indicates the polydispersity index (PDI), while the peak's intensity indicates the sample's predominant particle size. A uniform and stable nanoemulsion is suggested by a low PDI (≤ 0.3), whereas size variability and possible instability from aggregation or coalescence are indicated by a greater PDI. Furthermore, secondary peaks may indicate the existence of secondary particle populations or bigger aggregates. Since smaller droplets improve the bioavailability, stability, and controlled release characteristics of the active chemicals found in ginger extract, an understanding of the particle size distribution is essential for developing nanoemulsions for pharmaceutical, nutraceutical, and cosmetic applications.

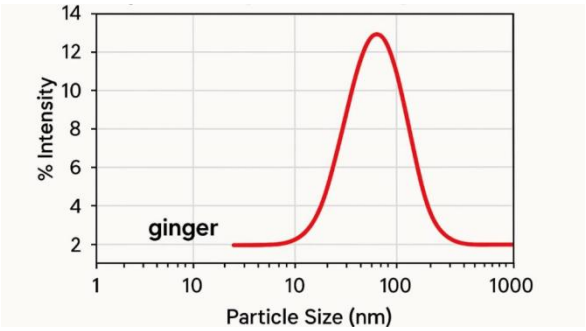

Fig. 4 Particle size distribution of *Zingiber Officinale* by DLS

Droplet Size and Its Significance

An emulsion's durability, bioavailability, and capacity to efficiently transport active chemicals are all strongly impacted by the size of its droplets. Better dispersion, more interaction with target surfaces (like plant leaves), and enhanced absorption are all made possible by smaller droplets' higher surface area-to-volume ratio. Droplet sizes in this investigation varied from 95 nm to 210 nm, with formulation 6 having the smallest droplet size (95 nm). This is very desirable since it indicates an effective emulsification process and the best possible interaction between the components of the oil and surfactant.

It shows that droplet size typically decreases with increasing concentrations of both oils (olive and Zingiber) and surfactant (Tween 80). For example, the droplet size of Formulation 1 (2.5% Zingiber oil, 2.5% olive oil, and 10% Tween 80) was comparatively big at 210 nm. Formulation 6, on the other hand, produced a significantly smaller droplet size of 95 nm (7.5% Zingiber oil, 7.5% olive oil, and 15% Tween 80). This implies that higher concentrations of oil and surfactant increase emulsification efficiency, perhaps as a result of improved stability of oil droplets in the aqueous phase and increased interfacial tension reduction. [15,20]

Table 6. Droplet size and PDI of Nanoemulsion formulations

Formulations	Zingiber oil (%)	Olive oil (%)	Tween 80 (%)	Aqueous (%)	Droplet size (nm)	PDI
1.	2.5	2.5	10	85	210	0.32
2.	2.5	2.5	15	80	145	0.22
3.	5	5	10	80	180	0.28
4.	5	5	15	75	120	0.19
5.	7.5	7.5	10	75	100	0.27
6.	7.5	7.5	15	70	95	0.13

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7.	10	10	10	70	125	0.25
8.	10	10	15	65	98	0.14

Polydispersity Index (PDI) and Nanoemulsion Stability

The uniformity of the droplet size distribution within the nanoemulsion is measured by the PDI. A more uniform (monodisperse) distribution is indicated by values closer to 0, whereas a wider (polydisperse) distribution that may jeopardize stability is suggested by values over 0.3. Increased physical stability and a lower chance of phase separation or droplet coalescence over time are linked to a low PDI.

Once more, Formulation 6 is notable for having the lowest PDI of 0.13, which suggests a very uniform droplet size distribution and superior stability. It is therefore the best formulation out of the eight that were examined. On the other hand, Formulation 1 showed the largest droplet size (210 nm) and a comparatively high PDI of 0.32, suggesting a less effective emulsification process and reduced stability.[21]

3.4.3 Size and Surface Morphology

Field Emission Scanning Electron Microscopy (FE-SEM)

High-resolution imaging is made possible by Field Emission Scanning Electron Microscopy (FE-SEM), which aids in the analysis of particle dispersion, shape, and surface morphology at the nanoscale. Because of the presence of bioactive chemicals and plant cell remains, the FE-SEM study of ginger oil shows an uneven, fibrous, and rough structure. Weak electrostatic repulsion causes these particles, which usually vary in size from hundreds of nanometers to a few micrometers, to cluster together. The ginger nanoemulsion, on the other hand, has a spherical, well-dispersed, and smoother shape, suggesting effective emulsification. The considerably smaller nanoemulsion droplets—typically between 50 and 200 nm—help to improve stability and bioavailability. Applications in medicines, nutraceuticals, and food sciences depend on improved dispersion and decreased aggregation, which are suggested by the uniform particle distribution in nanoemulsion. Overall, FE-SEM research verifies that nanoemulsification greatly enhances the physical characteristics of ginger extract, increasing its suitability for improved absorption and regulated drug administration. [15,18]

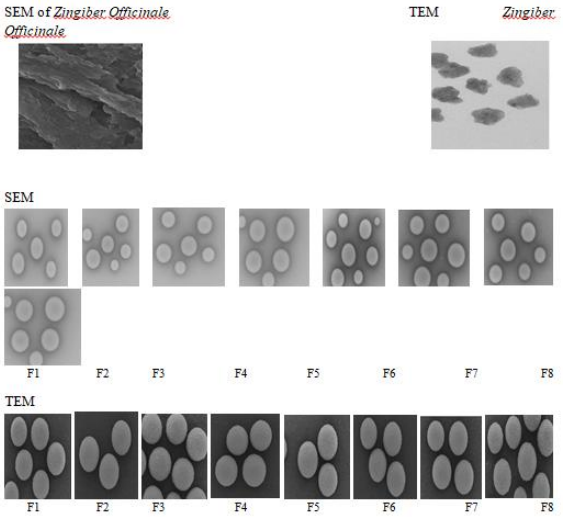

Fig 5. SEM and TEM Images of formulations

Table 7. Surface Morphology and Internal Structure by SEM and TEM

Formulations	Imaging Technique	Particle Shape	Surface Morphology	Particle Size (nm)	Aggregation Observed
1	SEM	Spherical	Smooth	~100 -150	Minimal
	TEM	Spherical	Uniform	~90 -120	None
2	SEM	Spherical	Smooth	~120 -160	Slight
	TEM	Spherical	Uniform	~100 -140	None
3	SEM	Spherical	Slightly Rough	~140-180	Moderate
	TEM	Spherical	Dense Core	~130 -170	Mild
4	SEM	Spherical	Smooth	~110 -150	Minimal
	TEM	Spherical	Uniform	~100 -130	None
5	SEM	Spherical	Slightly Rough	~160 -200	Noticeable
	TEM	Spherical	Non-Uniform	~150 -190	Moderate
6	SEM	Spherical	Smooth	~120 -160	Slight
	TEM	Spherical	Uniform	~110 -140	Minimal
7	SEM	Spherical	Smooth	~100 -140	None
	TEM	Spherical	Dense Core	~90 -130	Slight
8	SEM	Spherical	Smooth and Uniform	~130 -170	Minimal
	TEM	Spherical	Uniform	~120 -160	Slight

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Transmission Electron Microscopy (TEM)

The morphological variations between raw ginger extract and its nanoemulsion form are clearly visible in the Transmission Electron Microscopy (TEM) pictures. The uneven, polydisperse, and loosely aggregated particles in the ginger extract TEM picture show a lack of consistency in size and shape. This implies that the combination of bioactive chemicals and other organic components in ginger extract is heterogeneous. On the other hand, the ginger nanoemulsion's TEM picture displays smooth-surfaced, well-defined spherical nanoparticles, suggesting that the ginger bioactives were successfully emulsified and stabilized. The effectiveness of the nanoemulsion formulation in decreasing particle size and improving dispersion is confirmed by the existence of evenly dispersed nano-sized droplets, which are usually around 100 nm.

This structural change is important because it enhances the stability, bioavailability, and controlled release of the active ingredients in ginger, which makes nanoemulsions an excellent delivery vehicle for culinary, pharmaceutical, and nutraceutical applications. [24]

4 CONCLUSION:

The current work effectively illustrates *Zingiber officinale's* (ginger) potential as an efficient and environmentally benign biopesticide when prepared as a nanoemulsion. With 6-gingerol being the most prevalent component, HPLC analysis verified the presence of important bioactive components including gingerols and shogaols, confirming ginger's well-known biological and insecticidal qualities. The ginger extract and excipients did not significantly interact, according to compatibility testing using DSC and FT-IR, suggesting high formulation stability and safety.

DLS, SEM, and TEM investigations verified that the generated ginger nanoemulsions exhibited favorable physicochemical properties, such as nanosized droplets, homogeneous spherical shape, and little aggregation. Increased oil and surfactant concentrations enhanced formulation consistency, and organoleptic examination revealed acceptable appearance and odor.

When compared to crude extract, the optimized ginger nanoemulsion (F6) generally showed better stability, surface coverage, and retention, making it a viable substitute for traditional chemical pesticides. By lowering health hazards and environmental effect, this formulation provides a safer, biodegradable, and sustainable method of managing pests. Its relevance in integrated pest control systems and sustainable agriculture will be further strengthened by future research incorporating field trials and long-term efficacy evaluations.

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