

# Laboratory Evaluation of the Efficacy of Wild Thyme Oil (*Thymus syriacus* Boiss) and Its Nano-Formulations Using Silica Nanoparticles and Polyethylene Glycol Against the Two-Spotted Spider Mite (*Tetranychus urticae* Koch) (Acari: Tetranychidae)

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## Abstract

The two-spotted spider mite, *Tetranychus urticae* Koch, is considered one of the most dangerous agricultural pests worldwide due to its wide distribution, broad host range, and rapid development of resistance to chemical pesticides. These characteristics have made its control using conventional methods increasingly difficult, prompting the search for safer and more effective alternatives. As a result, research has shifted toward evaluating the efficacy of biopesticides derived from aromatic plants. In this study, the efficacy of wild thyme (*Thymus syriacus* Boiss.) essential oil and its nano formulations prepared using silica nanoparticles and polyethylene glycol (PEG) was evaluated for the control of *T. urticae* at different developmental stages (adult, protonymph, and egg). The experiments were conducted using the leaf disc dipping method, in which treated discs were immersed for 5 seconds in various concentrations of the essential oil (0.5%, 1%, 2%, and 4%) and its nano-formulations (100, 250, 500, 1000, 2000, and 3000 ppm). The results showed that mortality rates varied depending on the type of treatment, applied concentration, target stage, and the post-treatment period. The 4% concentration of thyme oil caused 100% mortality in both adult and protonymph stages from the fifth to the seventh day post-treatment. The 2% concentration also achieved high efficacy, with a maximum adult mortality rate of 87.14% on the seventh day, and 100% mortality of protonymphs starting from the fifth day. At a concentration of 2000 ppm, the thyme oil–nano-silica formulation induced female mortality rates of 34.67% on the first day, increasing to 97.14% by day seven. For the protonymph stage, mortality was 37.32% on day one and reached 100% from day five onward. In comparison, the PEG-based formulation at the same concentration exhibited a slower effect, with protonymph mortality rising from 28% on day one to 94.67% by day seven, while female mortality increased from 20% to 89.98% by the end of the trial. At a concentration of 3000 ppm, the nano-silica formulation exhibited a more rapid increase in efficacy during the initial days compared to the PEG-based formulation, which showed a more gradual effect. On day one, thyme oil–nano-silica induced mortality rates of 40% and 38.67% in protonymphs and females, respectively, whereas the PEG-based formulation caused equal mortality rates of 38.67% in both stages. As the experiment progressed, mortality continued to rise in both treatments, reaching 100% for both stages by day five. High-concentration treatments caused a noticeable delay in egg hatching. The essential thyme oil at 4% and 2% concentrations inhibited hatching by 76.87% and 73.98%, respectively. Meanwhile, the nano-silica and PEG-loaded formulations at 3000 ppm delayed hatching until the fifth day of the experiment, with inhibition rates of 67.38% and 62.45%, respectively. These results highlight the high efficacy of thyme oil and its nano-formulations, supporting their potential integration into integrated pest management (IPM).

**Keywords:** Two-spotted spider mite (*Tetranychus urticae*), Integrated pest management (IPM), Wild thyme oil (*Thymus syriacus*), Nanotechnology, Nano-silica, Polyethylene glycol (PEG), Biopesticides.



## 1. Introduction

Mites are among the most impactful agricultural pests affecting global plant production due to the significant economic and environmental damage they cause. Belonging to the order Acarina, these arthropods include a variety of species, some of which parasitize plants and feed on their sap. This feeding behavior reduces crop productivity and causes direct damage to plant tissues. Moreover, certain mite species are known vectors of viral pathogens or can induce complex physiological stress in plants (Kandel et al., 2022; Emam et al., 2021).

the two-spotted spider mite (*Tetranychus urticae* Koch) stands out as one of the most destructive agricultural pests worldwide. It infests more than 1,200 plant species from diverse families, including over 150 economically important crops across various sectors such as vegetables, fruits, and field crops (Ahmadi et al., 2021; Zeshan et al., 2024). Red spider mites cause annual productivity losses estimated at approximately 20–40% (Kumar et al., 2022). Their piercing-sucking mouthparts damage plant cells during feeding, leading to cellular breakdown and the appearance of necrotic spots due to chlorophyll depletion, which severely impairs photosynthesis (Nasr, 2021). Its notoriety stems from its high adaptability to different environments, rapid reproduction, and remarkable ability to develop resistance to conventional chemical pesticides—making it a persistent concern for farmers globally (Xu et al., 2018; Inak, 2019).

The issue of the two-spotted spider mite has escalated notably since the mid-20th century, due to a combination of factors. Chief among them is the extensive use of chemical pesticides, which has led to the decline of natural enemies, enabling unchecked mite population growth. Additionally, the expansion of intensive agriculture and increased diversity of host plants have created a favorable environment for mite proliferation year-round (Sakr, 1988). The over-reliance on synthetic chemical pesticides has further accelerated the development of resistance among mite populations, thereby significantly reducing the effectiveness of traditional control methods (Xu et al., 2018; Zhu et al., 2024).

Globally, an estimated 3 million tons of chemical pesticides are used annually for pest control. However, a large proportion of these chemicals fails to reach their intended targets after application and instead leach into surrounding environments polluting soil, water, and air (Wu et al., 2018). This contamination poses severe environmental and health risks, including acute and chronic poisoning in humans and non-target organisms, with approximately 385 million cases of pesticide poisoning reported annually and thousands of associated deaths (Boedeker et al., 2020). Furthermore, these issues are exacerbated by the phenomenon of "biomagnification," wherein pesticide residues accumulate along the food chain, causing long-term health effects and raising serious ecological concerns (Pérez-Lucas et al., 2019; Tongo et al., 2022).

In light of the environmental and health challenges associated with the use of chemical pesticides, the search for safe and environmentally friendly alternatives has become increasingly important. Essential oils extracted from plants have emerged at the forefront of these alternatives. In recent years, plant-based insecticides have gained growing attention as effective and safe options within integrated pest management strategies (Lima et al., 2020; Habashy et al., 2023).

Global studies have demonstrated that many plant-derived compounds exhibit moderate to high biological efficacy against a wide range of agricultural pests (Souto et al., 2021; Khursheed, 2022). Both the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have emphasized the importance of plants—including medicinal and aromatic species—as valuable sources of natural products for developing pharmaceutical drugs and eco-friendly pesticides. This underscores the need for further research to fully characterize their bioactive properties (Belmain et al., 2022).

Studies indicate that plant oils, particularly essential oils, are biodegradable biopesticides that exhibit high efficacy and relatively low environmental and health risks. Essential oils, especially those extracted from plants belonging to the Lamiaceae family such as (*Thymus vulgaris* and *Thymus syriacus*), have emerged as promising alternatives. These oils are rich in active compounds like thymol and carvacrol, which have demonstrated both repellent and toxic effects against various pests, including mites (Neves & Da Camara, 2016; Tak & Isman, 2017; Sakr et al., 2023).

These bioactive compounds operate through multiple mechanisms, including inhibiting mite development, reducing fertility, and disrupting feeding behavior. Additionally, essential oils have been shown to inhibit detoxifying enzymes in mites, such as glutathione S-transferases (GSTs), esterases (ESTs), cytochrome P450 enzymes, and acetylcholinesterase (AChE)—a key enzyme in neural transmission—resulting in neural dysfunction and pest mortality (Farahani et al., 2020; Souto et al., 2021). Such mechanisms position essential oils as promising components of Integrated Pest Management (IPM) programs (Benelli and Maggi, 2022).

Essential oils (EOs) are volatile organic compounds synthesized as secondary metabolites in plants, predominantly comprising terpenoids. These complex mixtures consist of multiple bioactive constituents (Sadgrove et al., 2022). Tests have shown that essential oils (EOs), particularly those belonging to the Lamiaceae family, possess multiple modes of action against pests, including repellency, antifeedant effects, fertility inhibition, respiratory suppression, growth retardation, and interference with the nervous system (Ma et al., 2020). The efficacy of plant-derived essential oils (EOs) has been evaluated against various arthropods, with some oils demonstrating high mortality rates in addition to strong repellent and antifeedant properties (Reddy & Dolma, 2018).

Aissaoui et al. (2018) evaluated the acaricidal efficacy of three essential oils (EOs), including *Thymus capitatus*, against *Tetranychus urticae*. The study assessed the toxic effects of these compounds on eggs, larvae, and adults, alongside chemical composition analysis using gas chromatography-mass spectrometry (GC-MS). The GC-MS results revealed that thyme oil contained multiple bioactive compounds, with carvacrol as the dominant constituent (55.95%). This compound exhibited strong adulticidal and larvicidal activity, achieving 100% mortality in adults and 97.7% in larvae at a 1% concentration.

A separate Moroccan study analyzed the EOs of three thyme species (*T. atlanticus*, *T. maroccanus*, and *T. saturoioides*), identifying key compounds such as borneol, thymol,  $\alpha$ -pinene, and p-cymene in the first species, while carvacrol,  $\alpha$ -pinene, and p-cymene were predominant in the latter two. The oils were tested via leaf-dipping (against adult females of *Eutetranychus orientalis*) and leaf-disc spraying (for ovicidal effects). All three thyme EOs demonstrated high efficacy against both adults and eggs of the target mite, supporting their potential in integrated pest management (IPM) programs (Mohamed et al., 2021).

However, the practical application of essential oils in field conditions faces several limitations, primarily due to their instability when exposed to environmental factors such as heat, and ultraviolet radiation. These conditions significantly reduce their post-application efficacy and longevity. To overcome this, nanotechnology-based encapsulation has emerged as an innovative solution, enhancing the performance of essential oils by protecting them within nano-sized carriers. These carriers allow for controlled, gradual release of active ingredients, thereby improving their persistence and reducing the required dosage (Benyacoub et al., 2019; Pavela & Benelli, 2016).

Nanotechnology is considered one of the modern and innovative solutions that contribute to reducing the use of chemical pesticides, minimizing their loss, and protecting crops from pests in a sustainable manner. This technology has been increasingly applied across various fields such as agriculture, environmental science, chemistry, and biomedical and biological applications (Camara et al., 2019; Kumar et al., 2021). Nanoparticles are regarded as a novel and safe alternative for pest control compared to conventional chemical pesticides (Marčić, 2021).

The term “nano” is derived from the Greek word meaning “dwarf.” Technically, however, “nano” refers to a scale of approximately  $10^{-9}$ , or one-billionth of a unit. Nanotechnology has significantly advanced through the use of particles ranging in size from 1 to 100 nanometers (Bhattacharyya et al., 2010).

Modern technologies in the production of nanoformulations contribute to enhancing the properties of plant extracts, which are environmentally friendly natural products. These enhancements include improved stability against light and heat, as well as reduced degradation losses caused by environmental factors. Consequently, these advancements improve the efficiency of pest control applications by significantly minimizing pesticide loss to the air up to 90% compared to conventional spraying methods. This reduction has had a positive impact by lowering environmental pollution levels and decreasing cases of toxicity among non-target organisms (Xiao et al., 2021; Sarkar et al., 2021).

Within the framework of modern plant protection programs leveraging interdisciplinary scientific advances, significant efforts are being directed toward employing nanopesticide formulations - particularly those of botanical origin - for controlling harmful pests while prioritizing public health and environmental safety (Ismail, 2022; Chojnacka, 2024). One of the main advantages of using nanoparticles is their ability to enhance the long-term stability of pesticides, in addition to improving the release of active compounds at the targeted site. This minimizes adverse effects on non-target organisms (Deshpande, 2019; Bhan et al., 2018). Furthermore, the unique properties of nanoparticles such as high permeability and extremely small size make them more effective against pests compared to conventional pesticides. These particles may also exhibit low toxicity to non-target organisms, making them a safer and more environmentally friendly alternative.

Innovative nano-pesticides are nanomaterials specifically designed to enhance plant protection, reduce application losses, and improve leaf surface coverage. They also contribute to increased pesticide stability and allow for reduced quantities to achieve the same level of efficacy. Nano-pesticide formulations vary and include metallic nanoparticles, active encapsulation components such as nanoemulsions, and polymeric nanoparticles (Chaud et al., 2021).

Many studies focus on the development of smart delivery systems for insecticides in the field, which involve the slow and sustained release of active ingredients. This approach enhances the solubility of poorly soluble compounds and protects them from premature degradation, thereby contributing to a reduction in the overall use of chemical substances (Gao et al., 2018; Mattos et al., 2019). Moreover, nanoparticles enhance the properties of water-insoluble pesticides by improving their dispersibility and reducing issues related to drift and leaching. This optimization increases their efficiency in targeting and interacting with the intended organisms (Syafudin et al., 2021).

Among nanocarriers, silica nanoparticles ( $\text{SiO}_2$ -NPs) are widely used due to their favorable physical and chemical properties, which enable them to penetrate the mite's cuticle and disrupt its physiological functions. This results in multiple lethal effects, including interference with neurological and metabolic processes (Emam et al., 2021; Rasim et al., 2021). Hollow porous silica nanoparticles (PHSNs) serve as smart delivery systems that shield active ingredients from environmental degradation and release them in a slow, controlled manner—extending protection duration and minimizing reapplication (Kumar et al., 2022). The efficacy of silica nanoparticles is largely attributed to their ability to absorb lipids from the mite's body, causing water loss and ultimately death by desiccation (El-Wahab & El-Bendary, 2016). Organosilicone compounds are commonly employed as surfactants in pesticide formulations to enhance efficacy, while also exhibiting inherent pesticidal properties. Chen et al. (2022) evaluated the toxicity and control efficiency of the spreading agent Silwet 408, against the two-spotted spider mite (*T. urticae*). At 1000 mg/L concentration, Silwet 408 achieved 96% mortality rate 24 hours post-application against both larval and adult stages, and 54% residual efficacy after 14 days.

Additionally, polyethylene glycol (PEG) is commonly employed in nanoencapsulation due to its biocompatibility and excellent physicochemical properties. PEG enhances the stability and efficiency of active compounds while reducing toxicity to non-target organisms (Granata et al., 2018; Adeyemi et al., 2023). Recent studies have demonstrated the effectiveness of PEG in improving pesticide performance, such as increasing the efficacy of encapsulated clofentezine against *T. urticae* while minimizing side effects (Ahmadi et al., 2021).

These advanced technologies highlight the potential for combining the biological efficacy of essential oils with the advantages of nanotechnology to develop eco-friendly and sustainable pest control solutions. Based on this perspective, the present study aims to evaluate the efficacy of wild thyme (*Thymus syriacus* Boiss) essential oil and its nanoformulations incorporating silica nanoparticles and PEG at varying concentrations against the two-spotted spider mite (*Tetranychus urticae* Koch) under controlled laboratory conditions. The objective is to propose highly effective natural alternatives that reduce dependence on chemical pesticides and support integrated pest management strategies.

## **1. Research Objectives and Significance**

This study contributes to the expanding field of sustainable pest management by exploring safe and effective natural alternatives to synthetic chemical pesticides. These alternatives can be utilized either independently or

integrated within comprehensive Integrated Pest Management (IPM) programs. The overarching goal is to reduce the environmental and health hazards commonly associated with conventional pesticides while improving the biological control of key agricultural pests, specifically the two-spotted spider mite (*Tetranychus urticae* Koch), which is recognized as one of the most destructive pests affecting crops globally.

The objectives of the current research are to:

- Assess the bioactivity of wild thyme (*Thymus syriacus*) essential oil at varying concentrations against multiple developmental stages of *T. urticae*.
- Develop and characterize nano-formulated bio-pesticides by incorporating wild thyme essential oil with silica nanoparticles (SiO<sub>2</sub>-NPs).
- Preparation of natural nano-pesticides based on wild thyme (*T. syriacus*) essential oil formulated with polyethylene glycol (PEG).
- Evaluate the efficacy of these nanoformulations on targeted life stages of the mite.
- Compare the performance of nano-encapsulated thyme oil formulations with that of the crude essential oil.

## 2. Materials and Methods

### 3.1. Test Organism

The two-spotted spider mite (*Tetranychus urticae* Koch) was selected as the test organism due to its wide distribution and severe impact on crops. This species is known for its broad host range, high reproductive potential, and ability to infest a wide variety of open-field and greenhouse crops (Tehri, 2014 ).

A pesticide-susceptible strain maintained in the laboratories of the Faculty of Agriculture for over 15 years without exposure to chemical treatments was used in all experiments. The study focused on various life stages of the mite, including adult females, protonymphs, and eggs, which were obtained from biology laboratory trials under controlled conditions (24±3°C, 60±5% RH, 12L:12D photoperiod).

Rearing was conducted in double-walled rearing trays with a water barrier between the walls to prevent mite escape. Infested plant material was collected from terminal plant parts and placed on healthy bean plants to replace deteriorated hosts. To ensure the safe disposal of infested material, old plant parts were soaked in water for 24 hours (Siddhapara &Virani, 2018).

### 3.2. Host Plant

Common bean plants (*Phaseolus vulgaris* L.) were selected as the host for mite propagation due to their proven compatibility with *T. urticae* and ease of cultivation under controlled laboratory conditions (Kumari et al., 2017). Seeds were initially germinated on filter paper within 15 cm diameter Petri dishes, then transplanted into small pots containing a homogeneous mixture of red soil, peat, and sand (equal parts). Each pot was sown with five seeds and watered daily over a three-week period until seedlings reached an appropriate developmental stage for experimental use.

### 3.3. Plant Material and Essential Oil Preparation

Wild thyme (*Thymus syriacus*) was chosen as a perennial aromatic plant with a strong scent. Its essential oil is primarily stored in the leaves (Küçükaydın et al., 2021).

Wild thyme samples were collected in May 2022, from uncultivated, pesticide-free areas in the rural region of Latakia, Syria. The leaves were carefully dissected from stems, then the leaves were shade-dried and ground into fine powder by the Blender.

### 3.4. Equipment and Instruments:

- Gas Chromatography–Mass Spectrometry (GC/MS), model:( Hewlett- packart)

- Clevenger-type apparatus
- UV-Visible Spectrophotometer
- Rotavapor (Heidolph, Germany) equipped with a water bath
- Votrex
- Blender
- Precision balance (d = 0.01 g, Sartorius, Germany)
- Standard laboratory glassware (beakers, Erlenmeyer flasks, separating funnels, tubes, etc.)

### 3.5. Chemical Reagents:

- n-Hexane
- Dichloromethane
- Distilled water
- Anhydrous sodium sulfate

**Acaricide** : Danikong (Pyflubumide)

### *Nanomaterials Used in the Study:*

1. Polyethylene Glycol (PEG 4000) Non-ionic polymeric compound, Molecular weight: 4000 Da, Work as Stabilizer and carrier matrix for nanoformulations Origin: Industrially sourced (India), Applications: Widely used in pharmaceutical and agricultural nanoformulations, Enhances solubility and dispersion of hydrophobic compounds.
2. Silica Nanoparticles (SiO<sub>2</sub> NPs). Source: Synthesized in the Laboratory of Agriculture Faculty, Latakia University, Size: Average diameter = 39.48 nm (confirmed by Scanning Electron Microscopy, SEM), (Al-Haik, 2023). Nanoparticulate carriers for controlled pesticide release, Improve adhesion and foliar uptake of bioactive compounds.

### 3.6. Essential Oil Extraction and Isolation:

The essential oil was extracted by hydrodistillation using a Clevenger-type apparatus, where 40 g of the aerial parts of air-dried aerial parts of *Thymus syriacus* were weighed and placed into a 5-liter flask, 2 liters of distilled water were added to it, and the extraction continued for 4 hours at 70°C. After cooling, the base oil was collected using a syringe and dried by adding sodium sulfate to remove water from the oil. The oil was collected after good mixing and separated by evaporation. The sample was transferred to a small brown bottle. It was closed tightly and kept in the refrigerator at 4°C for the time of analysis. By gas chromatography with mass spectrometry (GC/MS), the concentration of the essential oil was expressed as the number of milliliters obtained from the essential oil in relation to the dry weight, which amounted to 2.3 ml/100 g of dry weight, and the dry weight of the analyte was determined by taking a specific weight of the plant material and drying it for 24 hours in an oven at 105°C.

### 3.7. Technology Used in the Analysis of Essential Oils (GC/MS):

The chemical composition of the essential oils was determined using Gas Chromatography-Mass Spectrometry (GC-MS, Hewlett-Packard). The analysis was performed by Mixed 0.5 mL thyme essential oil with 1 mL dichloromethane (DCM). 1 µL aliquot injection into GC-MS system, equipped with a DB-5 capillary column (5% phenyl methyl siloxane), Length: 30 m, Internal diameter: 0.25 mm, Film thickness: 0.25 µm, Carrier Gas: Helium (1 mL/min flow rate). Injector: 250°C, Ion source: 230°C, Quadrupole: 130°C. Temperature Program: started 70°C, gradually rising: 4°C/min to reach 280°C, which remains for 10 min.

The essential oil components extracted from the aerial parts were identified by comparing the obtained mass spectra of each peak in the GC/MS chromatogram with those stored in the instrument's built-in spectral libraries (NIST and Wiley) (Sakr et al., 2023).

### 3.8. Preparation of Thyme Oil Concentrations:

Thymus syriacus essential oil was prepared in concentrations of 0.5%, 1%, 2%, and 4%. A 0.5% Tween 20% solution was used as the control.

- control standard: Danikong® (0.5 mL/L distilled water).

### 3.9. Preparation of Wild Thyme Oil with Nano-Silica:

Three grams of thyme essential oil were mixed with 10 ml of dichloromethane as Solvent. The mixture was vortexed to enhance initial homogenization., 3 grams of nano-silica were added, and the mixture was stirred continuously for 2 hours to ensure proper dispersion of the nanoparticles and uniform coating of the oil on the silica surface. It was then left overnight to allow the solvent to evaporate.

The next day, 1 liter of distilled water and 7 ml of Tween 20% were added. The mixture was stirred again using a vortex mixer well to obtain a stock solution with a concentration of 3000 ppm. From this stock, the following concentrations were prepared: 2000, 1000, 500, 250, and 100 ppm. Control: 0.3 g of nano-silica+ 0.7ml of Tween 20% , dissolved in 100 ml of distilled water.

### 3.10. Preparation of Wild Thyme Oil with Polyethylene Glycol (PEG):

Three grams of thyme oil were mixed with 12.6 grams of PEG and 2.5 ml of Tween 20, and the mixture was stirred continuously, Then, 1 liter of distilled water was added, and stirring was continued until complete mixing (homogenization) between the oil and water was achieved, until a stable emulsion was formed. This resulted in a stock solution of 3000 ppm, from which the same concentrations were prepared as above. Control: 1.26 ml of PEG + 0.25 ml of Tween 20 dissolved in 100 ml of distilled water.

### 3.11. Treatment Methods and Experimental Design:

The Leaf Disk Method was used for simplified application and observation (Kumari et al., 2017).

Experiments were conducted on three life stages of *T. urticae* (eggs, protonymphs, and adult females) under controlled laboratory conditions:

Temperature:  $24 \pm 3^\circ\text{C}$ , Relative Humidity:  $60 \pm 5\%$ , Photoperiod: 12:12 (light:dark). Each treatment consisted of 5 replicates, with 15 individuals per replicate for motile stages and 20 eggs per replicate.

Leaf disks (15 mm in diameter) were treated by immersion in the tested concentrations for 5 seconds, then allowed to dry to prevent mite drowning. Individuals were transferred using a fine brush. Egg bioassays were performed by allowing 5 adult females per replicate to oviposit for 3 hours. After oviposition, the disks containing the eggs were treated (Cavalcanti et al., 2010).

- *In all testes ,a standard chemical control using Danikong® (Pyflubumide), (0.5 mL/1L distilled water).*

### 3.12. Observation and Evaluation Criteria:

Observations were recorded daily for 7 days using a stereomicroscope (75x magnification), except for the fertility test, which lasted 5 days.

**Mortality rate** was the primary criterion for evaluating the efficacy of treatments, in addition to their impact on specific biological parameters such as:

- *Egg hatching*
- *Embryonic development*

- Time to adulthood

The mortality of motile mites was confirmed by the absence of movement in response to gentle stimulation with a fine brush, whereas egg mortality was determined based on visible shrinkage and the failure to hatch (Sakr, 1988).

### 3.13. Correction Equations and Statistical Analysis

*Abbott's formula (1925)* was used to calculate the percentage effect (mortality rate) and to evaluate the efficacy of the treatments against the protonymph and adult stages.

$$WG\% = \frac{C - T}{C} \times 100$$

Where:

*WG%* = Percentage effect (corrected mortality)

*C* = Number of live individuals in the control replicates

*T* = Number of live individuals in the treated replicates

To correct the effect of treatments on freshly laid eggs, *Schneider-Orelli's formula (1947)* was applied

$$WG\% = \frac{B - K}{100 - k} \times 100$$

Where:

*WG%* = Corrected effect percentage

*B* = Observed mortality (%) in the treatment group

*K* = Natural mortality (%) in the control group

### Statistical Analysis

The data were statistically analyzed using the R statistical software R (R Core Team, 2013). One-way analysis of variance (ANOVA) was employed to evaluate the effects, followed by Tukey's test to compare the means among the different tested concentrations. The treatments included, thyme oils, and nanoformulations of thyme oils loaded onto either nanosilica or polyethylene glycol. The analysis was conducted separately for each day of the experiment, with significance evaluated at the 1% level ( $P\text{-value} \leq 0.01$ ).

## 4. Results and Discussion

### 4.1. Evaluation of the Efficacy of Thymus syriacus Essential Oil on Egg Viability of Tetranychus urticae

Statistical analysis revealed highly significant differences ( $p < 0.01$ ) among the tested treatments from the beginning of the experiment, as shown in Table 1. Notably, the higher concentrations of wild thyme oil (4% and 2%) demonstrated egg hatch inhibition rates comparable to that of the standard pesticide (100%). Lower concentrations also showed considerable effectiveness, with inhibition rates of 79.97% at 1% concentration and 44.76% at 0.5%. Over time, a gradual decline in hatch inhibition was observed across all treatments, reaching 76.87% for the 4% concentration and 73.98% for the 2% concentration by the end of the experiment. These values were lower than the inhibition rate achieved by the standard pesticide, which remained at 96.84%.

The results showed that treatment with different concentrations of wild thyme oil had a clear effect on the hatching rate of newly laid *T. urticae* eggs. A direct correlation was observed between the concentration of the oil and the reduction in egg hatch rate, with higher concentrations resulting in greater inhibition compared to the control.

**Table 1:** Corrected egg hatch inhibition percentages (%), measured over 7 days following the treatment of newly laid *T. urticae* eggs with graded concentrations of wild thyme oil under laboratory conditions according to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ ) .

Formulation		Egg Hatch Inhibition Percentage (%) Over 7 Days Post-Treatment				
Species	Days	4	5	6	7	
	Concentration					
Thyme oil	4%	100a	86.18b	80.45b	76.87b	
	2%	100a	82.97b	78.85b	73.98b	
	1%	79.97b	71.90c	66.74c	54.72c	
	0.5	44.76c	41.60d	38.67d	35.15d	
Standard pesticide Danikong		100a	97.91a	96.71 a	96.84a	
Control treatment		16.47d	3.40e	4.07e	0.80e	
P- value		0.0000245***	0.0000216***	0.000078***	0.000089***	

#### 4.2- Evaluation of the Efficacy of Thymus syriacus Essential Oil on Adult Tetranychus urticae

The results revealed a significant effect of *T. syriacus* essential oil on adult females of *T. urticae* compared to the untreated control, as shown in Table 2. Statistically significant differences were observed among the tested treatments across all experimental days ( $P$ -value < 0.01). Mortality rates increased with both higher oil concentrations and longer exposure durations. Specifically, the 4% and 2% concentrations exhibited notable acaricidal activity, significantly outperforming other treatments during the first four days of the experiment, with recorded mortality rates ranging from 38.67% to 87.81% and 29.34% to 71.62%, respectively.

Although these effects were initially lower than those achieved by the standard chemical pesticide, the efficacy of the 4% thyme oil concentration increased markedly from the fifth day onward, ultimately reaching 100% mortality, thereby matching the performance of the reference pesticide.

**Table 2:** Effect of different concentrations of *Thymus syriacus* essential oil on the adult stage of *Tetranychus urticae* over 7 days, under laboratory conditions, calculated according to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ ) .

Formulation		Effect of graded concentrations of <i>T. syriacus</i> essential oil on the adult stage of <i>T.urticae</i> under laboratory conditions.						
Species	Days	1	2	3	4	5	6	7
	Concentration							
Thyme oil	4 %	38.67b	62.67b	79.71b	87.81b	100a	100a	100a
	2 %	29.34 bc	48 c	60.81 c	71.62c	77.03b	81.95b	87.14 b
	1 %	26.67 c	33.33 d	48.65d	59.46d	67.57c	70.83c	72.86c
	0.5 %	4 d	8e	17.57e	24.33e	29.73d	33.34d	37.14d
Standard pesticide Danikong		70.67 a	93.33a	100a	100a	100a	100a	100a
Control treatment		0d	0e	1.33f	1.33f	1.33e	4e	6.67e
P- value		0.0000421	0.0000224	0.000052	0.000066	0.000032	0.000045	0.0000216
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#### 4.3 Results of Evaluating the Efficacy of of Essential oil Thyme on the Protonymph Stage of *T.urticae*:

As shown in Table 3, the results demonstrated statistically significant differences between the wild thyme oil treatments and the untreated control ( $P \leq 0.01$ ). The acaricidal efficacy of thyme oil increased markedly with both concentration and time. On the first day of the experiment, the 2% and 4% concentrations exhibited effects comparable to the standard pesticide, with no significant differences observed among these treatments. However, on the second and third days, the chemical pesticide showed superior efficacy compared to both concentrations. Starting from day five through day seven, the mortality rates for the 2% and 4% thyme oil treatments increased

steadily, ultimately reaching 100%, thereby matching the performance of the standard pesticide. In contrast, the 1% concentration showed a gradual increase in mortality over time, reaching a maximum of 82.68% on day seven. The lowest concentration (0.5%) exhibited limited efficacy, with a progressive but modest increase in mortality that did not exceed 46.66% by the seventh day.

**Table 3:** Effectiveness of Different Concentrations of Wild Thyme Oil on the Protonymph Stage of *T.urticae* over 7 days, Under Laboratory Conditions, According to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ ).

Formulation		Effect of Varying Concentrations of Wild Thyme Oil on the Protonymph Stage of <i>T.urticae</i> Under Laboratory Conditions						
Species	Days	1	2	3	4	5	6	7
	Concentration							
Thyme oil	4 %	64.02a	66.70c	81.34b	93.30ab	100a	100a	100a
	2 %	58.68a	63.34c	75.98b	85.36b	100a	100a	100a
	1 %	22.68b	35.98d	48.02c	73.34c	81.34b	82.68b	82.68b
	0.5 %	0c	10.66e	22.68d	28d	32c	32c	46.66c
Standard pesticide Danikong		73.32a	95.98a	100a	100a	100a	100a	100a
Control treatment		0c	0f	0e	0e	2.68d	5.36d	6.68d
P-value		0.000011	0.0000224	0.000045	0.000028	0.000078	0.0000213	0.000068
		***		***	***	***	***	***

**4.4. Results of Evaluating the Efficacy of Essential oil Thyme Loaded on PEG on the Viability of *T. urticae* Eggs (Egg Stage):**

As illustrated in Table 4, the results revealed statistically significant differences among the tested treatments across all experimental days (P-value < 0.01). High concentrations of wild thyme oil (1000 ppm, 2000 ppm, and 3000 ppm) completely inhibited egg hatchability, achieving 100% suppression on the fourth day of treatment—comparable to the effect of the standard pesticide.

However, starting from day five, these concentrations showed a noticeable decline in hatch inhibition, without achieving complete suppression. By day seven, hatchability rates at 1000 ppm, 2000 ppm, and 3000 ppm reached 51.18%, 56.69%, and 62.45%, respectively. In contrast, lower concentrations (100 ppm, 250 ppm, and 500 ppm) exhibited relatively limited inhibitory effects on egg hatchability. On day seven, the recorded hatch rates were 3.28%, 14.52%, and 32.98%, respectively.

**Table 4:** Egg hatch inhibition rate (%) , over 7 days following the treatment of newly laid *T. urticae* eggs with graded concentrations of PEG-loaded wild thyme oil under laboratory conditions according to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Egg Hatch Inhibition Percentage (%) Over 7 Days Post-Treatment			
Species	Days	4	5	6	7
	Concentration				
Thyme oil	100 ppm	8.77e	7.44f	4.84g	3.28g
	250 ppm	24.47c	21.36e	18.98f	14.52f
	500ppm	50.54b	44.66c	40.85e	32.98e
	1000ppm	100a	58.79d	56.51d	51.18d
	2000ppm	100a	69.81b	62.93c	56.69c
	3000ppm	100a	73.80b	69.91b	62.45b
Standard pesticide Danikong		100a	96a	95.71a	95.04a
Control treatment		20.60d	17.20e	5.00g	4g
P- value		0.000026***	0.000087***	0.000066***	0.0000705***

#### 4.5. Results of Evaluating the Efficacy of Essential oil Thyme Loaded on PEG on the Adult Stage of *T. urticae*:

Table (5): illustrates the effect of various concentrations of wild thyme oil loaded on PEG on the adult stage of *T. urticae* under laboratory conditions, according to Abbott’s formula (Abbott, 1925).

The findings revealed that efficacy was positively correlated with both concentration and exposure time. On day one, the 3000 ppm concentration achieved a mortality rate of 38.67%, while lower concentrations showed negligible effects. Starting from day four, the highest concentration exhibited substantial efficacy, reaching 91.81%, and exceeding 100% on days six and seven—comparable to the efficacy of the standard acaricide "Danikong." Medium concentrations (1000–2000 ppm) displayed a steadily increasing but lower efficacy that did not reach the level of the standard acaricide. Conversely, low concentrations remained below the effective threshold.

**Table 5:** Effectiveness of Various Concentrations of Wild Thyme Oil Loaded on PEG Against the Adult Stage of *T. urticae* over a 7 day, Under Laboratory Conditions According to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Effect of Concentrations of of Essential oil Thyme Loaded on PEG on the Adult Stage of <i>T. urticae</i> Under Laboratory Conditions						
Species	Days	1	2	3	4	5	6	7
	Concentration							
Thyme Oil Loaded on PEG	100ppm	0e	2.67d	6.76ef	6.95a	8.40e	8.60e	8.60e
	250ppm	0e	8d	16.48e	29.38d	31.40d	32.87d	34.16d
	500ppm	5.33d	13.33d	23.40d	35.49d	46.85c	52.33c	55.03c
	1000ppm	10.69cd	32.67c	41.71cd	53.43c	69.94b	76.99b	82.92b
	2000ppm	20c	37.53c	44.40c	62c	75.67b	87.13ab	89.98ab
	3000ppm	38.67b	62.67b	53.52bc	91.81a	100a	100a	100a
Standard pesticide Danikong		70.66a	93.12a	100a	100a	100a	100a	100a
Control treatment		oe	1.34d	4.02f	5.36a	6.68e	6.68e	6.68e
P- value		0.000046	0.000048	0.0000216	0.0000224	0.000448	0.000414	0.000066
		***	***	***	***	***	***	***

#### 4.6. Results of Evaluating the Efficacy of of Essential oil Thyme Loaded on PEG on the Protonymph Stage of *T. urticae*:

Table (6): the results shown revealed statistically significant differences among the laboratory-tested treatments throughout all experimental days (P-value < 0.01). The efficacy of the formulation increased with both concentration and time. At 3000 ppm, the mortality rate reached 38.67% on the first day and increased progressively to achieve 100% by day five, matching the effectiveness of the standard pesticide. At 2000 ppm, mortality began at 28% on day one and rose to 94.67% by day seven. In contrast, lower concentrations such as 100 ppm and 250 ppm exhibited weak effects, with mortality rates not exceeding 12.77% and 41.33%, respectively, on the seventh day.

**Table 6:** Effectiveness of Various Concentrations of PEG-Loaded Wild Thyme Oil on the Protonymph Stage of *T. urticae* over a 7 day Under Laboratory Conditions, According to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Effect of Concentrations of PEG-Loaded Wild Thyme Oil on the Protonymph Stage of <i>T. urticae</i> Under Laboratory Conditions							
Species	Days	Concentration	1	2	3	4	5	6	7
			<i>Thyme Oil Loaded on PEG</i>	100ppm	oe	2.47e	6.83d	6.05e	8.84e
	250ppm	0e	16d	27.99cd	32d	36d	40d	41.33d	
	500ppm	10.67d	17.33d	46.57c	55.81c	58.57c	62c	62.88c	
	1000ppm	25.33c	40c	67.33ab	74.67b	74.67b	78,67b	84b	
	2000ppm	28c	53.33b	68.38b	89.15a	88a	89.33ab	94.67ab	
	3000ppm	38.67b	62.67b	53.52bc	91.81a	100a	100a	100a	
Standard pesticide									
Danikong		73.32a	95.98a	100a	100a	100a	100a	100a	
Control treatment		oe	Oe	2.68d	4.02e	4.02e	5.36a	6.68e	
P- value		0.00022	0.00034	0.0000277	0.0000212	0.0000448	0.000036	0.000074	
		***	***	***	***	***	***	***	

**4.7. Efficacy of Essential oil Thyme Loaded on Nano-Silica Against (Egg) of *T.urticae***

Table (7) indicates the presence of highly significant differences among the tested treatments in terms of egg hatch inhibition rates of the studied mite species under laboratory conditions throughout the experimental period (P-value < 0.01). Treatment with wild thyme oil loaded onto nano-silica resulted in complete inhibition of egg hatchability (100%) on the first day at concentrations of 1000 ppm, 2000 ppm, and 3000 ppm, matching the efficacy of the standard pesticide.

As the days progressed, hatch inhibition rates declined across treatments in varying degrees depending on concentration. By the final day, the highest inhibition was recorded at 3000 ppm (67.38%), followed by 2000 ppm (61.17%) and 1000 ppm (58.21%). The standard pesticide maintained a significantly superior effect, with a hatch inhibition rate of 95.04%.

**Table 7:** Corrected egg hatch inhibition percentages (%), measured over 7 days following the treatment of newly laid *T. urticae* eggs with graded concentrations of wild thyme oil under laboratory conditions according to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Egg Hatch Inhibition Percentage (%) Over 7 Days Post-Treatment				
Species	Days	Concentration	4	5	6	7
			<i>Thyme Oil Loaded on Nano-Silica</i>	100 ppm	24.91d	27.33f
	250 ppm	44.24c	41.24e	37.47e	28.96e	
	500ppm	59.52b	56.52d	52.40d	46.70d	
	1000ppm	100a	76.66c	63.20c	58.21c	
	2000ppm	100a	84.57b	66.51c	61.17c	
	3000ppm	100a	86.14b	78.51b	67.38b	
Standard pesticide						
Danikong		100a	96a	95.71a	95.04a	
Control treatment		17e	9g	4.20g	0.62g	
P- value		0.0000216***	0.000076***	0.00068***	0.000034***	

**4.8. Efficacy of Essential oil Thyme Loaded on Nano-Silica Against (Adult) of *T. urticae***

The data presented in Table (8) indicate highly significant differences (P-value < 0.01) among the tested treatments in their effects on adult *T. urticae* under laboratory conditions across all days of the experiment. Wild thyme oil

encapsulated in nano-silica exhibited progressively increasing efficacy against newly emerged adult individuals of *Tetranychus urticae*. Mortality rates rose steadily with both higher concentrations and longer exposure durations. At 3000 ppm, the treatment showed mortality rates ranging from 38.67% on the first day to 100% during the final three days, matching the performance of the standard pesticide in the latter stages of the experiment. The 1000 ppm and 2000 ppm concentrations began with mortality rates of 28% and 34.67%, respectively, on day one, and both exceeded 90% by day seven, indicating strong acaricidal potential at moderate concentrations.

**Table 8:** Effectiveness of Different Concentrations of Essential oil Thyme Loaded on Nano-Silica Against the Adult Stage of *T.urticae* over 7 days Under Laboratory Conditions According to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Effect of Different Concentrations of Essential oil Thyme l Loaded on Nano-Silica on the Adult Stage of <i>T.urticae</i> Under Laboratory Conditions						
Species	Days	1	2	3	4	5	6	7
	Concentration							
Thyme Oil Loaded on Nano-Silica	100ppm	od	3.91e	9.81e	24.67e	32.86c	33.90c	35.71c
	250ppm	od	20.38d	31.43d	38.57d	41.43c	42.86c	45.71c
	500ppm	21.33c	47.14c	54.29c	58.57c	61.43b	65.71b	67.14b
	1000ppm	28bc	52.68bc	63.51bc	72.60b	84.57 b	87.72 a	90.68 a
	2000ppm	34.67b	59.52b	73.14b	89.05ab	91.81a	95.91a	97.14a
	3000ppm	38.67b	67.62b	81.62b	91.81ab	100a	100a	100a
Standard pesticide Danikong		70.66a	93.12a	100a	100a	100a	100a	100a
Control treatment		od	1.34e	1.34e	1.34f	1.34d	6.70d	6.70d
P- value		0.0000212 ***	0.000442 ***	0.000022 ***	0.0000142 ***	0.000052 ***	0.0000215 ***	0.000044 ***

#### 4.9. Efficacy of Essential oil Thyme Loaded on Nano-Silica Against (prtonymph) of *T. urticae*

As shown in Table (9): The results presented in Table 9 demonstrate a significant acaricidal effect of nano-silica-loaded wild thyme oil on the protonymph stage of *Tetranychus urticae*, with statistically significant differences observed among treatments ( $P < 0.001$ ). Treatments at 2000 ppm and 3000 ppm achieved mortality rates of 37.32% and 40%, respectively, on the first day, reaching 100% from day five through day seven, indicating complete lethality at higher concentrations. In contrast, lower concentrations showed minimal or no efficacy. Treatments at 100 ppm and 250 ppm recorded 0% mortality on day one, and only reached 38.58% and 42.88%, respectively, by day seven, highlighting their limited acaricidal potential.

**Table 9:** Effectiveness of Different Concentrations of Essential oil Thyme Loaded on Nano-Silica Against the protonymph Stage of *T. urticae* over 7 days Under Laboratory Conditions According to Tukey’s HSD test at a 1% significance level ( $\alpha = 0.01$ )

Formulation		Effect of Different Concentrations of Wild Thyme Oil Loaded on Nano-Silica on the Protonymph Stage of <i>T.urticae</i> Under Laboratory Conditions						
Species	Days	1	2	3	4	5	6	7
	Concentration							
Thyme Oil Loaded on Nano-Silica	100ppm	O d	6.68ef	14.66f	22.36cd	32.86d	37.16d	38.58d
	250ppm	O d	18.66e	32e	33.72c	38.58d	41.44d	42.88d
	500ppm	25.34c	48d	52d	59.98b	62.68c	65.34c	69.34c
	1000ppm	32c	58.68c	74.44c	61.28b	86.68b	88.66 b	90.68b
	2000ppm	37.32bc	66.68bc	80bc	93.34a	100a	100a	100a
	3000ppm	40b	73.34b	85.34b	95.40a	100a	100a	100a
Standard pesticide Danikong		73.32a	95.98a	100a	100a	100a	100a	100a
Control treatment		O d	O f	O g	4.02d	5.36e	6.70e	6.70e
P- value		0.0000456	0.0000288	0.000055	0.0000206	0.0000216	0.0000556	0.0000557

## 5. Discussion

Recent findings from this study revealed that wild thyme essential oil exhibits notable biological activity against various developmental stages of *T. urticae*. These results are consistent with previous research indicating the oil's high efficacy across multiple life stages of the *T. urticae* (Aissaoui et al., 2018; Mostafa et al., 2025).

The observed bioactivity is primarily attributed to the presence of potent phenolic compounds, particularly thymol and carvacrol. These constituents have demonstrated the ability to penetrate cellular membranes, leading to disruptions in essential physiological processes such as cellular respiration and ion homeostasis. Such disturbances result in either mortality or developmental inhibition (Tak & Isman, 2017; Kaveh et al., 2025).

In addition to thymol and carvacrol, other volatile compounds including  $\gamma$ -terpinene, linalool, p-cymene, and  $\alpha$ -pinene contribute synergistically to the overall pesticidal effect of the oil (Mohamed et al., 2021; Yoon & Tak, 2025).

Although the oil's action at higher concentrations showed a delayed onset compared to the standard chemical pesticide, its efficacy became comparable by the fifth day post-treatment. Furthermore, the oil maintained a high mortality rate for up to 14 days following application, underscoring its potential as a sustainable alternative or complementary agent in Integrated Pest Management (IPM) strategies (Chen et al., 2022; Thomidis & Damos, 2024).

The results of this study indicated that encapsulating wild thyme essential oil in a carrier substance such as polyethylene glycol (PEG) led to a slow release of its active constituents. This controlled release resulted in a reduced biological efficacy against the studied developmental stages of *T. urticae*, in comparison to the unformulated (raw) oil, which exhibited higher mortality rates throughout the experimental period. This outcome can be attributed to the rapid release of active compounds from the raw oil, allowing them to quickly reach the biological target and induce immediate and direct toxic effects. In contrast, the PEG-based delivery system facilitated a gradual release of these compounds, thereby extending the duration of their activity (Fotoukkaia et al., 2020). Such a release profile may be advantageous in applications that require long-term efficacy without the need for repeated treatments—particularly in extended biological control systems or under unstable environmental conditions where the persistence and stability of the active ingredient over time are critical.

Encapsulation of wild thyme essential oil within nano-silica particles resulted in superior acaricidal efficacy against the nymphs, adult females, and eggs of *T. urticae*, compared to its formulation with polyethylene glycol (PEG). This enhanced performance is attributed to several interrelated factors.

Nano-silica is characterized by its highly porous structure and large surface area, which allows for greater loading capacity of active compounds and facilitates their rapid and efficient release upon contact with the pest or exposure to environmental triggers such as humidity and temperature (Zhao et al., 2020; Zhang & Chen, 2020).

Moreover, nano-silica contributes to improved adhesion to biological surfaces, including the chitinous exoskeleton of the mite, thereby prolonging the residence time of the active compound and increasing the likelihood of penetration into target tissues (Liu et al., 2021). In addition to its role as a carrier, nano-silica particles exert a direct mechanical effect on the pest by absorbing the protective wax layer of the cuticle, leading to water loss, desiccation, and ultimately enhanced mortality (Zayed, 2022).

In contrast, while PEG has hydrophilic nature may render it more susceptible to rapid removal from plant surfaces or the pest's body. Therefore, combining wild thyme oil with a nano-silica delivery system presents a promising strategy for improving pest control efficiency, especially against resistant life stages such as eggs (Rasim et al., 2021).

In this study, the chemical pesticide Danikong was employed as a control standard. It demonstrated high mortality rates against various developmental stages of *T. urticae*, outperforming certain treatments in specific trials. This elevated efficacy is attributed to the mode of action of its active ingredient, pyflubumide, which functions as a mitochondrial complex II inhibitor—a relatively novel and targeted mechanism that remains effective even against mite strains resistant to conventional acaricides.

However, despite its potency, recent studies have raised concerns regarding the potential for resistance development following intensive and repeated use of pyflubumide. (Fotoukkaia et al., 2020) reported that continuous exposure of multiple *T. urticae* strains to pyflubumide across successive generations resulted in a marked decline in sensitivity and the emergence of high resistance levels, with resistance ratios exceeding 600-fold. This phenomenon was linked to the upregulation of cytochrome P450 enzymes involved in the metabolic detoxification of the active compound.

These findings underscore the limitations of relying exclusively on chemical pesticides in pest management programs, as such practices may compromise long-term efficacy and sustainability. Consequently, there is a pressing need to adopt alternative, more resilient strategies.

In this context, nano-formulated thyme oil emerges as a promising candidate. Its demonstrated biological activity against multiple life stages of *T. urticae*, coupled with its environmental safety profile, positions it as a viable natural acaricide. Integrating such botanical formulations into pest control regimes can diversify the sources of selective pressure on the pest population, thereby mitigating the risk of resistance development. This approach enhances the effectiveness and sustainability of Integrated Pest Management (IPM) programs, aligning with ecological safety and long-term agricultural resilience (Benelli & Maggi, 2022).

## **6. Conclusion**

- The essential oil of thyme (*Thymus Syriacus*) exhibited notable biological efficacy against various developmental stages of *T. urticae*. Its application resulted in significant mortality rates, growth inhibition, and reduced egg hatchability, particularly at higher concentrations. These effects highlight its potential as a natural acaricide with multi-target action.
- Nanoformulations of thyme oil—especially those synthesized using nano-silica carriers—demonstrated superior bioactivity and stability compared to the crude essential oil. The increased surface area, controlled release properties, and improved penetration associated with nanocarriers contributed to enhanced acaricidal performance and prolonged residual activity.
- The use of nano-silica as a carrier material significantly enhances the release dynamics of active compounds in thyme essential oil. This improvement translates into faster and more stable acaricidal effects compared to the crude oil or formulations loaded onto polyethylene glycol (PEG). The nano-silica matrix facilitates better dispersion, controlled release, and increased bioavailability of the active constituents.
- The high efficacy of nano-encapsulated essential oils underscores their potential as eco-friendly alternatives to synthetic pesticides. Their integration into Integrated Pest Management (IPM) programs supports reduced reliance on conventional chemical acaricides, thereby promoting environmental safety, minimizing resistance development, and enhancing long-term sustainability in pest control strategies.

The results of the present study demonstrated that the essential oil of *T. syriacus* possesses promising biological activity against various developmental stages (*T. urticae*). The oil contributed to reducing egg hatchability, survival, and reproduction rates to varying degrees depending on concentration and exposure time.

Encapsulation of the oil using nano-silica particles or PEG polymer significantly enhanced its efficacy and persistence, with the nano-silica-based formulation showing superior performance in terms of rapid action and sustained biological effect compared to other treatments.

These findings suggest that nanotechnology is a powerful tool for improving the efficiency of plant-derived essential oils as bio-pesticides. It helps overcome challenges related to environmental instability and rapid degradation, and opens new avenues for developing safe and eco-friendly formulations within Integrated Pest Management (IPM) programs. Nevertheless, since these results were obtained under laboratory conditions, there is an urgent need for extensive field trials to evaluate the practical performance of these formulations under real environmental conditions. Such trials would validate their long-term biological efficacy and practical applicability, paving the way for their adoption as effective and sustainable alternatives to conventional chemical pesticides in agricultural pest management.

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## تقييم مخبري لكفاءة زيت الزعتر البري (*Thymus syriacus* Boiss) وتراكيبه المحضرة باستخدام النانو سيليكات والبولي إيثيلين جليكول بتراكيز مختلفة ضد الأكاروس الأحمر ذو البقعتين (*Tetranychus urticae* Koch) (Acari:Tetranychidae)

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### الملخص:

يُعدّ الأكاروس الأحمر ذو البقعتين *Tetranychus urticae* Koch من أخطر الآفات الزراعية على مستوى العالم، نظراً لانتشاره الواسع، وتعدد عوائله النباتية، وسرعته في تطوير مقاومة للمبيدات الكيميائية. وقد أدت هذه الخصائص إلى صعوبة السيطرة عليه بالوسائل الكيميائية التقليدية، مما استدعى البحث عن بدائل أكثر أماناً وفعالية، فكان الاتجاه نحو دراسة تأثير المبيدات الحيوية المستخلصة من النباتات العطرية. تمّ في هذه الدراسة تقييم فاعلية زيت الزعتر البري (*Thymus syriacus* Boiss) وتراكيبه النانوية المحضرة باستخدام جسيمات السيليكات النانوية وبوليمر البولي إيثيلين جليكول (PEG)، في مكافحة أطوار حياتية مختلفة (الإناث البالغة، الطور الحوري الأول، البيض) للأكاروس الأحمر. نُفذت التجارب باستخدام طريقة تغطيس الأقراص الورقية المعاملة حيث عُملت الأقراص لمدة ٥ ثوانٍ بتراكيز متدرّجة من الزيت (٥، ٢، ١، ٤ %)، ومن التراكيب النانوية (١٠٠، ٢٥٠، ٥٠٠، ١٠٠٠، ٣٠٠٠، ٢٠٠٠ ppm). أظهرت النتائج أن معدلات القتل تباينت تبعاً لنوع المعاملة والتركيز المطبق والطور المستهدف إضافة للزمن. إذ حققت المعاملة بزيت الزعتر الأساس (٤%) نسبة قتل بلغت ١٠٠% لكل من الإناث و الطور الحوري الأول بدءاً من اليوم الخامس وحتى نهاية التجربة، في حين حقق التركيز ٢% أعلى معدل قتل لكل من الإناث ٨٧، ١٤% و ١٠٠% للطور الحوري الأول بدءاً من اليوم الخامس. سجلت معاملات زيت الزعتر-نانو سيليكات عند التركيز ٢٠٠٠ ppm معدلات قتل للإناث بلغت ٦٧، ٣٤% في اليوم الأول من التجربة ووصلت إلى ٩٧، ١٤% في اليوم السابع، و ٣٧، ٣٢% للطور الحوري في اليوم الأول و ١٠٠% بدءاً من اليوم الخامس وحتى نهاية التجربة، بالمقابل وعند نفس التركيز سجلت المعاملة المحمّلة على PEG معدلات قتل بدأت ٢٨% للطور الحوري الأول في اليوم الأول ووصلت إلى ٩٤، ٦٧% في اليوم السابع، وعند الإناث بدأت ٢٠% ووصلت إلى ٨٩، ٩٨% في اليوم الأخير. أما عند التركيز ٣٠٠٠ ppm اتّسمت معاملة النانو سيليكات بتزايد أسرع في الفاعلية خلال الأيام الأولى، مقارنةً بمعاملات PEG، والتي أظهرت نمط تأثير أكثر تدرّجاً، حيث سجلت معاملة زيت الزعتر-نانو سيليكات في اليوم الأول معدلات قتل بلغت ٤٠% و ٣٨، ٦٧% للحوريات والإناث، على التوالي، بالمقابل سجلت معاملة زيت الزعتر-PEG معدلات قتل بلغت ٣٨، ٦٧% للحوريات والإناث على حدّ سواء. مع التقدم في أيام التجربة استمرت معدلات القتل بالارتفاع في كلا المعاملتين، لتبلغ ١٠٠% لكلا الطورين بحلول اليوم الخامس. بالنسبة لتجارب فقس البيوض، أظهرت المعاملات ذات التراكيز المرتفعة تأخيراً واضحاً في الفقس، حيث سجل زيت الزعتر الأساس بالتركيز بين ٤ و ٢% منعاً للفقس بنسب بلغت ٧٦، ٨٧% و ٧٣، ٩٨%، على التوالي، أما معاملات زيت الزعتر-نانو سيليكات و PEG فقد سجلت عند التركيز ٣٠٠٠ ppm تأخيراً للفقس كان أعلاه في اليوم الأول ١٠٠% وانخفض تدريجياً حتى اليوم الخامس بنسب بلغت ٦٧، ٣٨ و ٤٥، ٦٢%، على التوالي. تُشير هذه النتائج إلى الفعالية العالية لزيت الزعتر وتراكيبه النانوية، مما يدعم إمكانية دمجها ضمن برامج مكافحة المتكاملة للآفات، مع ضرورة تأكيد هذه النتائج من خلال تجارب حقليّة موسّعة.

**الكلمات المفتاحية:** الأكاروس الأحمر ذو البقعتين (*Tetranychus urticae*)، الإدارة المتكاملة للآفات (IPM)، زيت الزعتر البري (*Thymus syriacus*)، تقنية النانو، السيليكات النانوية، البولي إيثيلين جليكول (PEG)، المبيدات الحيوية.