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Mosquito repellency of carvacrol, thymol, and cinnamaldehyde nanogels against *Aedes aegypti*: a comparative study with DEET

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Abstract

Aedes aegypti is a primary vector of arboviral diseases, including chikungunya, dengue fever, yellow fever, and Zika virus. Given the increasing global burden and the limitations of synthetic repellents, there is a growing need for safe and effective botanical alternatives, especially in endemic regions. This study formulated thymol-, carvacrol-, and cinnamaldehyde-loaded nanoemulsions via spontaneous emulsification and subsequently gelled using hydroxypropyl methylcellulose (HPMC). Viscosity and encapsulation efficiency were assessed using viscometry and Attenuated Total Reflection-Fourier Transform Infrared (ATR-FTIR) spectroscopy. The repellent efficacy of the resulting nanogels against *Ae. aegypti* was assessed and benchmarked against DEET (40% w/v). The nanoemulsions exhibited particle sizes of 208 ± 5 nm, 183 ± 6 nm, and 193 ± 4 nm for thymol, carvacrol, and cinnamaldehyde, respectively. Among all formulations, carvacrol-based nanogel (3% w/v) demonstrated the longest protection time (250 ± 34 min), exceeding the commercial DEET formulation (190 ± 17 min). These findings highlight the potential of HPMC-based nanogel repellents, particularly those containing carvacrol, as effective and safer botanical alternatives to conventional repellents, with promising implications for integrated vector management strategies.

Keywords Nanoformulations, Botanical repellent, Vector control, Aedes aegypti

1 Introduction

Mosquitoes are major vectors of life-threatening diseases, affecting billions of people worldwide each year. Mosquito-borne illnesses cause nearly one million deaths annually, underscoring the urgency of effective vector control strategies [1]. Among these vectors, *Aedes aegypti* and *Aedes albopictus* transmit arboviruses such as dengue, yellow fever, chikungunya, and Zika. Of these, *Ae. aegypti* (Diptera: *Culicidae*) is the most efficient vector, particularly for dengue, due to its strong preference for human hosts and adaptability to urban environments. Even at low population densities, *Ae. aegypti* remains the primary driver of dengue transmission, closely linked to rapid urbanization [2, 3].

Dengue fever is currently the most widespread arboviral disease, with cases rising significantly in recent years. In 2023, global dengue cases peaked at over 6.5 million, with more than 7,300 related deaths reported across 80 countries in all WHO regions [4]. Mosquito repellents play a crucial role in reducing human-mosquito contact, thereby preventing the transmission of vector-borne diseases. While conventional control measures, such as insecticides and environmental management, are essential, topical repellents offer immediate and accessible personal protection, especially in endemic regions [4].

However, concerns over synthetic repellents' safety, toxicity, and environmental impact, especially N, N-diethyl-meta-toluamide (DEET), have increased interest in plant-based alternatives [5, 6]. Natural compounds such as carvacrol, cinnamaldehyde, and thymol have shown promising repellent activity, offering a safer and eco-friendly alternative to synthetic chemicals. Carvacrol, a monoterpenoid phenol in *Origanum vulgare*, *Zataria multiflora*, and *Thymus vulgaris*, has potent antimicrobial and insecticidal properties. It disrupts mosquito neurological function and acts as a contact and spatial repellent [7, 8]. Cinnamaldehyde, the main component of *Cinnamomum* species, exhibits significant larvicidal and repellent activity by interfering with insect olfactory receptors [8, 9]. Thymol, another phenolic compound found in thyme and oregano, is recognized for its broad-spectrum antimicrobial and insect-repelling effects, with high volatility and pungent odor that deters host-seeking behavior [8, 10].

Despite their potential, these bioactive compounds face challenges due to their hydrophobicity and volatility, limiting their stability and duration of action. Researchers have turned to nanoemulsion-based delivery systems to address these issues and improve solubility, stability, and sustained release [11, 12]. Nanoemulsions, characterized by droplet sizes typically below 200 nm, offer enhanced transdermal absorption, improved dispersion, and extended efficacy of hydrophobic actives [13, 14]. To further optimize their application and retention on the skin, nanoemulsions can be gelled using agents such as hydroxypropyl methylcellulose (HPMC), enhancing their viscosity, spreadability, and user compliance [15, 16].

In this study, we developed and evaluated HPMC-based nanogels loaded with thymol, carvacrol, and cinnamaldehyde for their repellent efficacy against *Aedes aegypti*. Their performance was compared with a commercial DEET (40% w/v) formulation.

2 Materials and methods

2.1 Materials

Thymol, carvacrol, cinnamaldehyde, and Tween 20 were purchased from Merck Chemical Company (Germany), while hydroxypropyl methylcellulose (HPMC) was obtained from Sigma-Aldrich (USA). A commercial repellent containing 40% DEET, commonly used in Iran, was acquired from Reyhan Naghsh Jahan Pharmaceutical Company.

Repellency tests were conducted using 5–7-day-old, non-blood-fed, nulliparous female *Aedes aegypti* mosquitoes (Bandar Abbas strain), provided by the *Culicidae* Insectary of the School of Public Health, Hormozgan University of Medical Sciences, Iran. Mosquitoes were reared in 40 × 40 × 40 cm cages under controlled environmental conditions (27 ± 2 °C, 70 ± 5% relative humidity, 12-hour light/dark cycle). Before the experiments, mosquitoes were starved for 14 h by removing the 10% sugar solution from their cages.

2.2 Preparation of nanoemulsion-based nanogels

Nanoemulsions were prepared via spontaneous emulsification. A mixture of carvacrol, cinnamaldehyde, and thymol (each at 3% w/v) was combined with Tween 20 (5% w/v) and stirred until homogeneous. Distilled water was added dropwise to bring the final volume to 20 mL, followed by continuous stirring for 40 min using an Alpha stirrer (Iran) at 2000 rpm and room temperature. The resulting nanoemulsions were subjected to droplet size analysis.

To prepare nanogels, HPMC (3% w/v) was gradually added to the nanoemulsions and stirred overnight at room temperature to promote gelation (Under the conditions mentioned). The resulting formulations were designated as **C.NGel**: carvacrol-containing nanogel, **CA.NGel**: cinnamaldehyde-containing nanogel, and **T.NGel**: thymol-containing nanogel. A blank nanogel **(NGel)** was also prepared using the same protocol but without active compounds.

2.3 Characterization of nanoemulsion-based nanogel

The nanoemulsions were characterized using dynamic light scattering (DLS; SZ – 100, Horiba, Japan) to determine droplet size, polydispersity index (PDI), SPAN (size distribution), and zeta potential. Optimal formulation parameters were defined as a droplet size < 200 nm, PDI < 0.7, and SPAN < 1.

Nanogel viscosity was measured using a rotational rheometer (MCR-302, Anton Paar, Austria) at shear rates ranging from 0.1 to 100 s^{-1}. Encapsulation efficiency and presence of active compounds were confirmed using Attenuated Total Reflection-Fourier Transform Infrared (ATR-FTIR) spectroscopy (Tensor II, Bruker, Germany) over a spectral range of 400–4000 cm^{-1}. Spectra were obtained for individual compounds and all nanogel formulations (NGel, C.NGel, CA.NGel, and T.NGel).

2.4 Investigation of repellent properties of nanogels

Repellent efficacy was assessed using the standard WHO arm-in-cage method [17]. A 22-year-old female volunteer disinfected her forearm with 70% ethanol. A defined 8 × 12.5 cm area on the inner forearm was treated with 1 g of each formulation (C.NGel, CA.NGel, T.NGel, or DEET 40%).

After a 5-min drying period, the treated arm was inserted into a cage containing 250 female *Ae. aegypti* mosquitoes for 3 min. This process was repeated at 30-min intervals until the first mosquito landed on the exposed skin. The volunteer's other forearm served as a negative control. Before and during the tests, the volunteer's forearm was exposed to the test cage for 30 s every hour. The count of mosquitoes landing on or attempting to bite the forearm (landing and probing) had to be at least 10 within 30 s for the test to be valid; otherwise, it was repeated. Each test was conducted in triplicate, and protection times were expressed as mean ± standard deviation. Statistical significance between formulations was analyzed using the Kruskal-Wallis test. Pairwise comparisons were performed using the Mann-Whitney U test with Bonferroni correction, with a confidence level of $p < 0.05$.

3 Results

3.1 Characteristics of the prepared nanogels

Figure 2 presents the dynamic light scattering (DLS) profiles of the blank nanoemulsion (NGel) and nanoemulsions loaded with thymol, carvacrol, and cinnamaldehyde. The average droplet sizes were measured as 8 ± 3 nm for NGel, 208 ± 5 nm for T.NGel, 193 ± 4 nm for C.NGel, and 183 ± 6 nm for CA.NGel. The SPAN values for all formulations were below 1, specifically 0.41, 0.38, 0.36, and 0.45, respectively, indicating a narrow size distribution. The polydispersity index (PDI) values were 0.007 for NGel, 0.46, 0.70, and 0.56 for T.NGel, C.NGel, and CA.NGel, respectively, confirms uniform and suitable size characteristics.

Figure 3 illustrates the zeta potential values of the nanogels, measured as − 1.5 ± 0.26 mV for NGel, − 56 ± 3 mV for T.NGel, − 43 ± 1 mV for C.NGel, and − 7 ± 1 mV for CA.NGel. The strongly negative zeta potentials of T.NGel and C.NGel indicate good colloidal stability. In contrast, CA.NGel exhibited a notably lower zeta potential (−7 ± 1 mV), suggesting comparatively lower electrostatic stability. Nevertheless, it is important to note that CA.NGel demonstrated satisfactory physical stability during the entire test period; however, its long-term stability may still require further investigation and monitoring under different storage conditions.

The rheological behavior of the nanogels is depicted in Fig. 4. All formulations exhibited a decrease in viscosity with increasing shear rate, demonstrating shear-thinning (pseudoplastic) behavior. This property is advantageous for topical application, facilitating ease of spreadability. The apparent viscosity values at a low shear rate of 0.1 s^{-1}, which approximate the zero-shear viscosity, were measured as follows: NGel 5032 mPa·s, T.NGel 71,444 mPa·s, C.NGel 23,200 mPa·s, and CA.NGel 4035 mPa·s. These values further illustrate the consistency differences among the formulations and support their stability and suitability for topical use.

3.2 ATR-FTIR

The study conducted ATR-FTIR analysis to investigate potential interactions among the components of the prepared nanogels. Figure 5 displays the ATR-FTIR spectra of HPMC (A), thymol (B), carvacrol (C), cinnamaldehyde (D), blank nanogel (NGel) (E), thymol

Fig. 1 **A** an exposed area with mosquitoes, **B** an exposed area on the volunteer's forearm in the cage

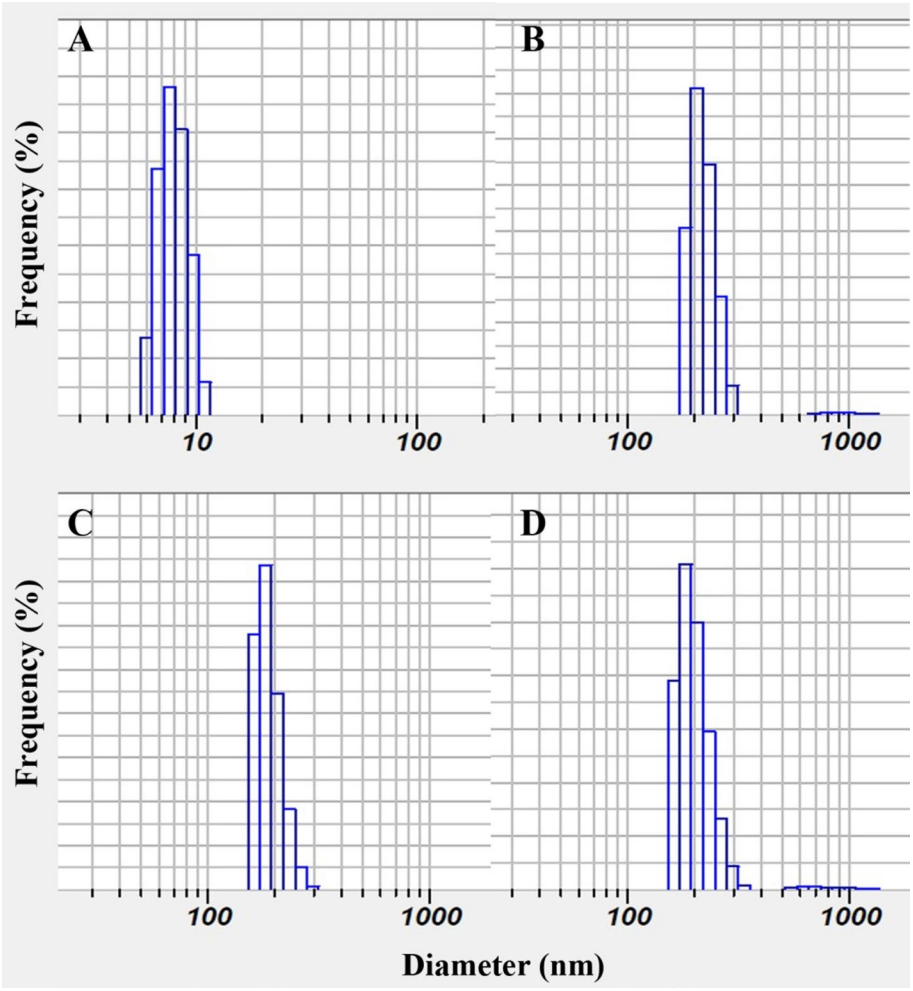

Fig. 2 DLS profiles of blank nanoemulsions (**A**) and nanoemulsions containing thymol (**B**), carvacrol (**C**), and cinnamaldehyde (**D**)

nanogel (T. NGel) (F), carvacrol nanogel (C. NGel) (G), and cinnamaldehyde nanogel (CA. NGel) (H). In the ATR-FTIR spectrum of HPMC, the absorption peak at 2901 cm^{-1} corresponds to CH2 stretching. The bands at 1052 and 3241 cm^{-1} are attributed to the stretching frequencies of C-O and O-H groups, respectively. Another peak at 1375 cm^{-1} is related to the bending vibration of the hydroxyl (-OH) group. Previous studies have reported similar characteristic peaks for HPMC [18, 19]. The spectrum of thymol shows a characteristic band at 3178 cm^{-1} assigned to the stretching vibration of the -OH group involving hydrogen bonding. Phenolic compounds like thymol are often characterized by the C = C stretching of the benzene ring, resulting in a moderate FTIR peak in the range of 1584 and 619 cm^{-1}. The absorption peaks at 1378 and 1359 cm^{-1} correspond to the stretching vibration of the isopropyl methyl group. The para-substituted phenyl is associated with the peak in the range of 1004 to 1057 cm^{-1}, while the strong band at 803 cm^{-1} is attributed to the ring vibration of thymol. The absorption peak at 3035 cm^{-1} is assigned to the =C–H group, while the stretching vibrations at 2957, 2926, and 2867 cm^{-1} correspond to the –CH group [20, 21]. The ATR-FTIR spectrum of carvacrol exhibits two absorption peaks at 2959 and 3379 cm^{-1}, attributed to the stretching vibration of the C = C–C and O–H groups, respectively. The 2869 and 2926 cm^{-1}

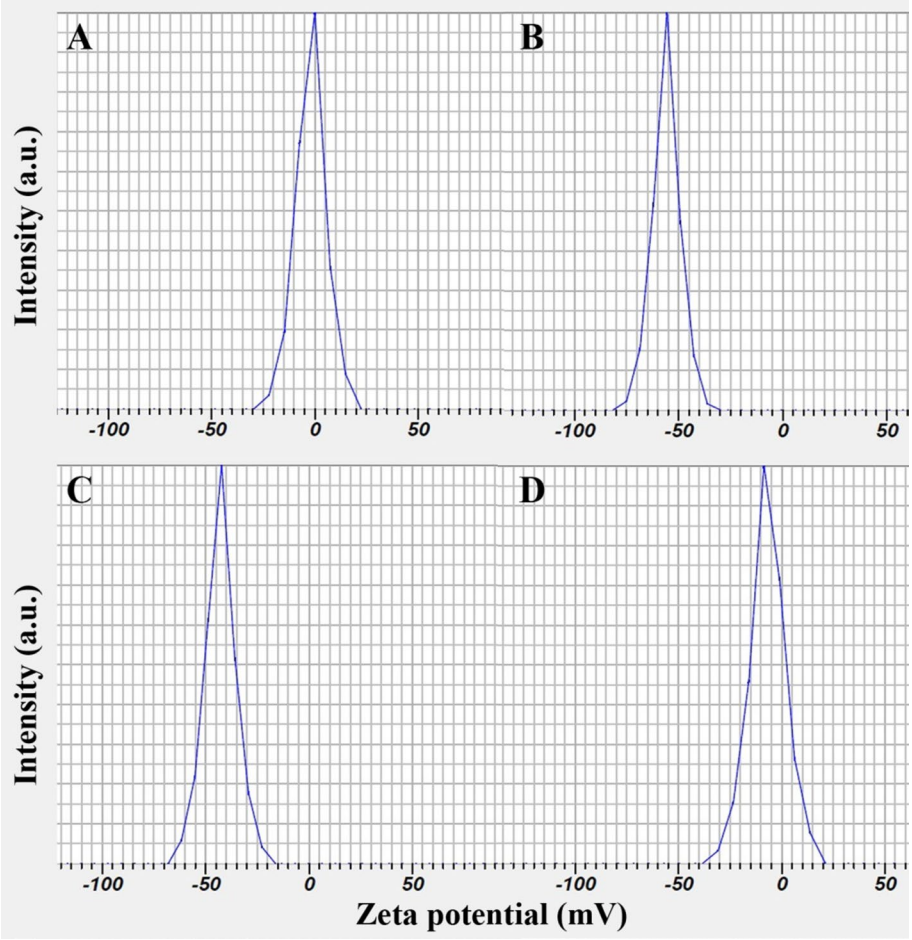

Fig. 3 The zeta potential of blank nanoemulsion (**A**) and nanoemulsion containing thymol (**B**), carvacrol (**C**), and cinnamaldehyde (**D**)

peaks are attributed to the symmetric and asymmetric stretching vibration of -CH2-, respectively.

The absorption peak around 1588 and 620 cm^{-1} is attributed to the C = C stretching vibration in the ATR-FTIR spectra of carvacrol. The intense peak at 811 cm^{-1} is related to the typical aromatic ring of carvacrol, caused by out-of-plane CH wagging vibrations. Key characteristic peaks of pure carvacrol are observed at 1249, 1173, 1115, 993, and 864 cm^{-1} [22, 23]. The ATR-FTIR spectrum of cinnamaldehyde shows a prominent peak at 1671 cm^{-1}, which is attributed to the carbonyl group C=O. Another characteristic peak at 1623 cm^{-1} is due to the aromatic benzene ring in conjugation with the alkene. The absorption peaks at 1449 and 575 cm^{-1} are associated with the C=C group. The bands at 3060 cm^{-1}, 3027 cm^{-1}, and 2988 cm^{-1} correspond to the stretching vibration of aromatic C–H, =C–H group, and C–H of the carbonyl group, respectively. The characteristic peak at 1160 cm^{-1} is related to aromatic C–H stretching vibration [24, 25]. The ATR-FTIR spectrum of the NGel shows a broad peak at 3483 cm^{-1}, attributed to the stretching vibration of O–H groups due to hydrogen bonding between Tween 20 and water. The absorption peak at 2924 cm^{-1} is attributed to the stretching vibration of the C-H bonds. The characteristic peak at 1733 cm^{-1} corresponds to the stretching of the carbonyl (–C=O) group, indicating the presence of the –C=O group in Tween 20. The

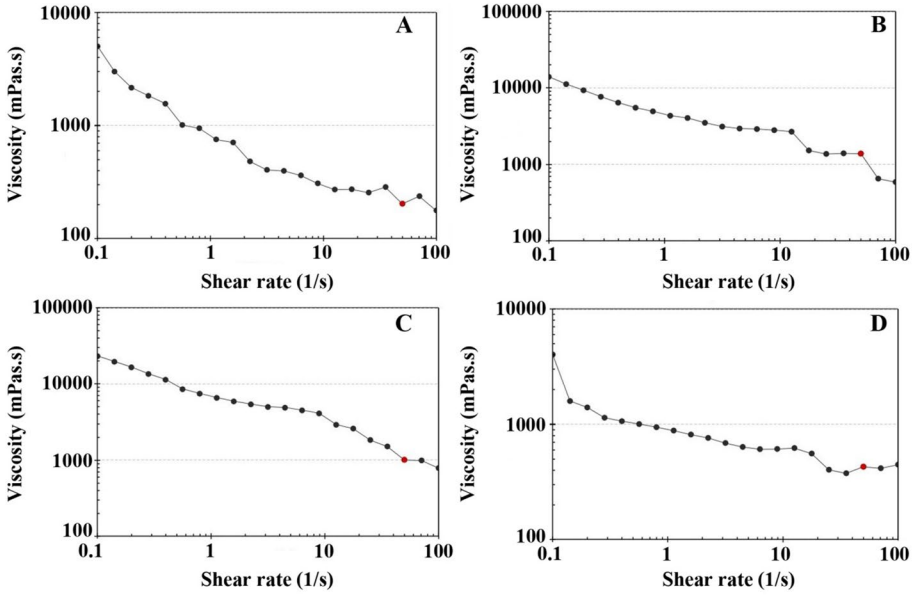

Fig. 4 Viscosity profiles of blank nanogel (**A**) and nanogels containing thymol (**B**), carvacrol (**C**), and cinnamaldehyde (**D**) (NGel, T.NGel, C.NGel, and CA.NGel)

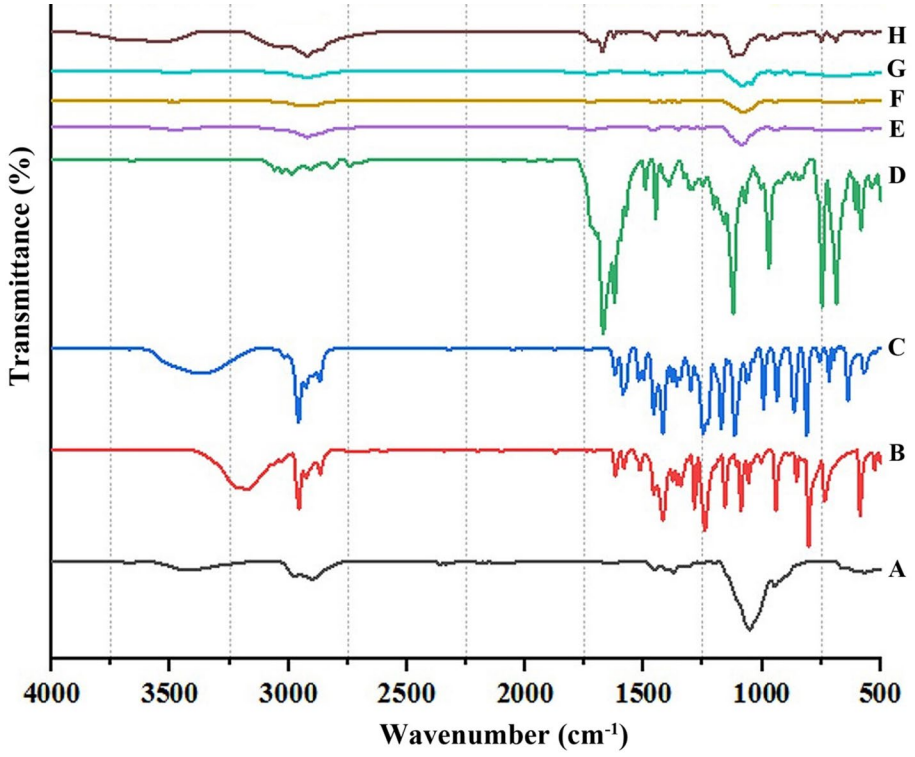

Fig. 5 ATR-FTIR spectra of HPMC (**A**), thymol (**B**), carvacrol (**C**), cinnamaldehyde (**D**), blank nanogel (**E**), and nanogels containing thymol (**F**), carvacrol (**G**), and cinnamaldehyde (**H**) (NGel, T.NGel, C.NGel, and CA.NGel)

intense peak at 1085 cm^{-1} is associated with the stretching of the C–O. The shifting of the prominent peaks in the ATR-FTIR spectrum of the gel indicates molecular interactions between HPMC and Tween 20. The ATR-FTIR spectrum of T. NGel shows a broad peak ranging from 3482 to 3687 cm^{-1}, indicating the presence of hydroxyl (-OH) groups

and hydrogen bonding between water, Tween 20, HPMC, and thymol. The band at 2924 cm^{-1} is related to the stretching of C-H, confirming the presence of HPMC, thymol, and Tween 20 in the nanogel formulation. The absorption peak at 1725 cm^{-1} verifies the carbonyl (C = O) group in the structure of Tween 20. The prominent peak at 1079 cm^{-1} is assigned to the stretching vibration of C–O [26]. In the ATR-FTIR spectrum of T. NGel, the characteristic peaks of all components of the nanogel are present with slight changes in the position and intensity of some peaks, indicating possible intermolecular interactions. The ATR-FTIR spectrum of C-NGel exhibits an extensive peak around 3490–3701 cm^{-1}, attributed to OH groups and possible hydrogen bonding between 20, HPMC, water, and carvacrol. The absorption peak at 2925 cm^{-1} is assigned to the stretching vibration of C–H, indicating the presence of Tween 20, HPMC, and carvacrol. The characteristic peak at 1722 cm^{-1} corresponds to the stretching of C=O, demonstrating the presence of the C=O group in Tween 20. The strong peak at 1084 cm^{-1} is related to the stretching of the C-O. The shifts in the position of the peaks are due to intermolecular interactions and the formation of hydrogen bonds between components of the final nanogel [8]. The ATR-FTIR spectrum of CA. NGel shows a broad peak ranging from 3545 to 3680 cm^{-1}, resulting from OH groups and hydrogen bonding between Tween 20, water, HPMC, and cinnamaldehyde. The absorption peaks at 2924 and 3029 cm^{-1} are assigned to the stretching of C-H, confirming the presence of cinnamaldehyde, Tween 20, and HPMC. The characteristic peak at 1705 cm^{-1} corresponds to the stretching vibration of the carbonyl C=O group present in the chemical structure of Tween 20 and cinnamaldehyde. The intense peak at 1094 cm^{-1} is related to the stretching of the C–O. The ATR-FTIR peaks of CA.NGel confirms the presence of all components in the final formulation [27, 28].

3.3 Repellent effect

Figure 6 shows the protection times of DEET (40% v/v), NGel (blank), and the nanogel formulations against *Ae. aegypti* mosquitoes. The recorded protection times were as follows: DEET, 190 ± 17 min; NGel, 0 ± 0 min; T.NGel, 240 ± 0 min; C.NGel, 250 ± 34 min; and CA.NGel, 200 ± 34 min.

The nanogels containing carvacrol, thymol, and cinnamaldehyde (each at 3% w/v) demonstrated more extended protection than DEET. However, one-way ANOVA analysis showed no statistically significant differences ($P > 0.05$) between DEET and the active nanogel formulations. As expected, the blank nanogel exhibited no repellent activity.

4 Discussions

This study used carvacrol, cinnamaldehyde, and thymol as natural mosquito repellents. These selected terpenes have already been widely reported for their repellent properties. However, their pure forms are unsuitable for direct application due to several limitations. Some are semi/solid at room temperature, while others are highly viscous, oily, or possess a strong and unpleasant odor that hinders practical usability. Furthermore, simple ethanol-based solutions of these terpenes are not ideal for topical application, as they lack suitable consistency, stability, and long-lasting efficacy on the skin. Given these constraints, the focus of this study was not to reassess the innate repellency of the terpenes themselves, but rather to explore the potential of a nano-formulated delivery system designed to overcome the limitations of their conventional forms. By encapsulating

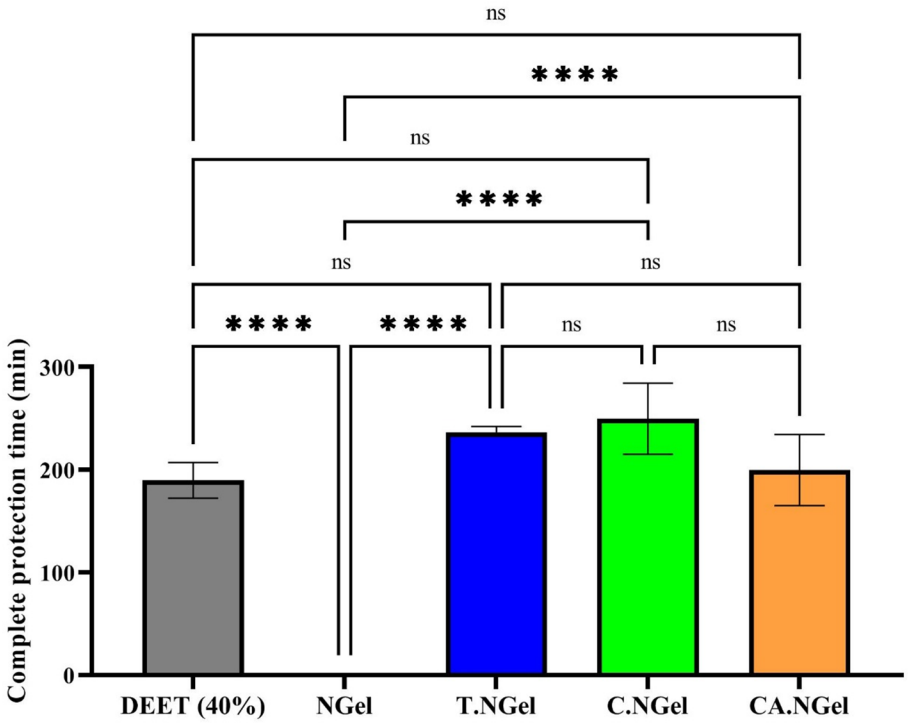

Fig. 6 Repellent activity of DEET 40% (commercial sample), blank nanogel, and nanogels containing thymol, carvacrol, and cinnamaldehyde (NGel, T.NGel, C.NGel, and CA.NGel) against *Ae. aegypti*. Data are presented as mean ± SD

the terpenes in a nanocarrier system, we aimed to improve their physical characteristics, enhance user acceptability, and potentially increase repellent efficacy.

This study successfully developed HPMC-based nanogels containing carvacrol, cinnamaldehyde, and thymol, demonstrating prolonged repellent efficacy (>120 min) against *Ae. aegypti*. Previous research has investigated nanostructured formulations of these bioactive compounds, such as antimicrobial carvacrol nanoemulsions, cinnamaldehyde-loaded nanoliposomes for food packaging, and thymol-chitosan nanogels [29–31]. However, HPMC-based systems remain underexplored despite their notable advantages. Our findings address this gap by harnessing HPMC's unique physicochemical properties to enhance both repellent efficacy and formulation usability.

The repellent activities of thymol, carvacrol, and cinnamaldehyde arise from multimodal mechanisms. These compounds disrupt mosquito olfactory receptors, masking host-seeking cues, and interfere with neurotransmission via GABA receptor modulation [32, 33]. They penetrate the insect cuticle at higher concentrations, disrupting cellular membranes and metabolic pathways. Behavioral studies have further demonstrated that these compounds induce avoidance behavior and inhibit oviposition, contributing to both immediate and long-term vector control [34–36]. Carvacrol and thymol are believed to trigger avoidance by activating olfactory receptor neurons involved in odor detection [37, 38].

Additionally, neurotoxic effects have been reported, including acetylcholinesterase (AChE) inhibition by carvacrol and thymol, leading to reduced motor function and impaired host-seeking behavior [38, 39]. The compounds' volatility also facilitates the formation of a spatial repellent barrier, deterring mosquito approach [40]. The irritant

properties of cinnamaldehyde contribute to its repellent efficacy, provoking immediate avoidance responses and potentially disrupting olfactory signals [41, 42].

Recent advances in nanoformulations of essential oils exemplify the growing interest in botanical insecticides. For instance, solid lipid nanoparticles loaded with *Zataria multiflora* essential oil enhanced protection against *Anopheles stephensi* by 300%, extending efficacy to 90 min compared to non-encapsulated oil [43]. Similarly, thymol nanoliposomes showed potent larvicidal activity (LC_{50}: 20 µg/mL) against *Ae. aegypti* [44]. In comparison, carvacrol nanoliposomes achieved an LC_{50} of 11.45 µg/mL against *An. stephensi*, outperforming free carvacrol substantially (LC_{50}: 128.65 µg/mL) [45]. These results highlight how nanoencapsulation enhances the bioactivity of plant-derived compounds. Our HPMC nanogels build upon this foundation, offering extended protection and supporting their potential as commercial repellent candidates [46]. Future research should evaluate their efficacy against other mosquito vectors, such as *Anopheles* and *Culex* species.

Our findings are consistent with trends in essential oil nanoformulation research. For example, nanoemulsions of *Mentha piperita* and *Eucalyptus globulus* essential oils provided 257–351 min of protection against *A. stephensi* [47, 48], while *Elettaria cardamomum* essential oil nanogels offered 63 ± 15 min of efficacy [49]. Nanoemulsions containing *Cymbopogon nardus*, *Ficus glomerata*, and citronella essential oils showed protection times of around 168–234 min against *Ae. aegypti* [50, 51].

Nanogels in this study were prepared from the initial nanoemulsions. Tween 20 concentrations were optimized to achieve two main objectives: maintaining particle size and distribution within a suitable range across all formulations and ensuring consistency of formulation components for valid comparisons. After extensive optimization trials, a 5% (w/v) Tween 20 concentration was determined to be optimal for achieving a stable particle size distribution and ensuring comparability across formulations. This choice was critical for balancing stability and comparability.

A key innovation in this study is using HPMC as a gelling agent instead of conventional polymers like carboxymethyl cellulose (CMC), which is commonly used in nanoemulsions [52]. HPMC offers superior solubility, thermal stability, and mechanical resilience, contributing to formulation robustness under diverse environmental conditions. Its tunable viscosity allows precise control over rheological properties and release kinetics of the repellent compounds [53]. Furthermore, HPMC exhibits inverse thermoreversible gelation, forming gels upon heating and reverting to sols upon cooling, enabling potential stimuli-responsive applications [54, 55]. Its biocompatibility, non-irritant nature, smooth and non-greasy texture, and high transparency enhance user compliance. These properties help overcome limitations of essential oil-based repellents, such as high volatility and poor aesthetics, while protecting the actives from oxidative degradation [56, 57].

Additionally, HPMC nanogels provide controlled release of volatile compounds such as carvacrol, cinnamaldehyde, and thymol via polymer hydration, swelling, and erosion mechanisms [58–60]. The nanogel matrix forms a viscous barrier that slows compound diffusion and shields the actives from rapid degradation and evaporation. This leads to a biphasic release pattern: an initial burst release from the surface followed by sustained diffusion from the polymer network [61–63]. As a result, nanoencapsulation prolongs the availability of active repellents near the skin, extending protection beyond 120 min.

By slowing evaporation and diffusion, the nanogels maintain an effective spatial repellent barrier, enhancing both immediate and long-lasting mosquito repellency [64, 65].

A notable limitation of our study is using a single human volunteer during repellent testing. This was an intentional choice to reduce inter-individual variability and maintain consistency during the screening phase, especially since physiological factors such as sweat composition and skin microbiota can significantly influence mosquito attraction [5, 66]. Our primary aim was to identify promising formulations with superior efficacy, and a controlled single-subject design facilitated this goal. However, this approach limits the generalizability of the results across different ages, genders, and environments. For broader clinical and public health relevance, future studies must include diverse human participants and evaluate efficacy under varying environmental conditions and against multiple mosquito species. This staged approach, from controlled screening to broader validation, will strengthen translational potential and support product development.

5 Conclusion

Nanogels incorporating 3% carvacrol, thymol, and cinnamaldehyde were successfully formulated as natural mosquito repellents. These nanogels provided protection times of 250 ± 34, 240 ± 0, and 200 ± 34 min, respectively, against *Ae. aegypti*, comparable to commercial DEET. The simple formulation process requires no advanced equipment, supporting practical applicability. Our results suggest that HPMC-based nanogels represent effective, natural alternatives for mosquito repellent development, with potential for further testing against other vector species. Given their low-cost preparation, favorable safety profile, and extended protection, these formulations could be practical interventions for mosquito-borne disease prevention, especially in endemic and resource-limited settings.

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Author contributions
SGh prepared the nanogels. ASD performed the repellent bioassays. MS interpreted the ATR-FTIR spectra. MNGh, SS, and MO contributed to manuscript drafting. MO designed the study and analyzed the data. All authors read and approved the final manuscript.

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Data availability
The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study involved a human volunteer but was not a clinical trial. The investigation was limited to evaluating botanical mosquito repellents on human skin following WHO guidelines. A 22-year-old female volunteer participated in the study after receiving a complete explanation of the repellent assay procedure. Written informed consent was obtained from the participant prior to testing. The corresponding author provided continuous monitoring during the test and followed up for one month to assess any potential adverse effects; no side effects were reported. All experimental procedures were approved by the Ethics Committee of Fasa University of Medical Sciences under the code IR.FUMS.REC.1403.066, and were conducted following institutional guidelines and national regulations.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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