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REGULAR ARTICLE

Development of Multifunctional Textiles with Mosquito Repellent and Antibacterial Properties Using Microencapsulated Lemongrass Essential Oil on Cotton–Polyester Fabric

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Abstract

This study presents an eco-friendly approach to developing multifunctional textiles by incorporating microencapsulated lemongrass essential oil (LEO) onto cotton–polyester blended fabrics. The treated fabrics were designed to exhibit mosquito repellent, antibacterial, and aromatic properties, offering a natural alternative to conventional synthetic finishes. LEO microcapsules were synthesized using the complex coacervation method and applied to the fabric via the pad-dry-cure method. The morphology of the microcapsules was analyzed using optical microscope, while the treated fabric was examined with scanning electron microscope (SEM). The functional performance of the treated fabric was evaluated through the arm-in-cage test, antibacterial assays, and sensory evaluation. Results showed that fabrics treated with 15% LEO microcapsules achieved 88% mosquito repellence efficacy protection before washing and 59% after 30 washing cycles, demonstrating durable functionality. The treated fabrics also maintained effective antibacterial activity and pleasant aroma retention. This study highlights a sustainable and eco-friendly finishing strategy for producing bio-functional textiles with potential applications in healthcare, outdoor wear, and wellness-related clothing.

Keywords Microcapsule · Lemongrass essential oil · Functional finishing · Mosquito repellent · Complex coacervation

1 Introduction

The escalating incidence of mosquito-borne diseases, including malaria and dengue fever, constitutes a major and growing threat to public health on a global scale [1]. These diseases, transmitted through the bites of infected mosquitoes, affect hundreds of millions of individuals worldwide, leading to significant morbidity and mortality. In Malaysia, the severity of this issue is underscored by the Ministry of Health's report of 123,133 dengue cases in 2023, highlighting the substantial impact of the disease on the nation's health [2]. Dengue fever not only causes widespread illness but also contributes to a concerning number of deaths, highlighting the urgent need for effective prevention and control measures. As dengue is endemic in Malaysia, the persistent presence of the *Aedes aegypti* mosquito, recognized as the primary vector for transmitting the dengue virus, further complicates efforts to manage and mitigate the disease's impact on the population.

According to the World Health Organization (WHO), conventional mosquito bite prevention methods include indoor insecticide spraying and the use of insecticide-treated nets [3]. In addition, repellents have been recognized as a key component of integrated strategies for controlling insect-borne diseases [4]. However, most commercial repellents rely on synthetic chemicals, such as N, N-diethyl-meta-toluamide (DEET), allethrin, N, N-diethyl mendelic acid amide, and dimethyl phthalate [5]. These compounds are associated with adverse effects, including skin irritation, allergic reactions, and potential neurological and cardiovascular issues, as well as harmful interactions with synthetic fabrics and plastics [6]. The frequent use of synthetic chemical repellents for mosquito control has disturbed natural ecosystems

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and contributed to insecticide resistance, mosquito population resurgence, and adverse impact on non-target organisms [7]. These drawbacks highlight the need for natural, safer repellent alternatives that are both effective and environmentally sustainable.

In response, the textile industry has shown growing interest in the functionalization of fabrics to provide added value through health, wellness, and comfort properties. Functional textiles go beyond the traditional role of offering esthetics and basic protection. They are specifically designed to deliver additional benefits or functions to the wearer or environment, such as moisture control, UV protection, antimicrobial activity, temperature regulation, or even health monitoring. Notably, the use of essential oils in textiles has emerged as a promising approach owing to their natural composition and multifunctional properties, such as antimicrobial, antioxidant, and aromatherapeutic effects [8]. Lemongrass (*Cymbopogon sp.*) essential oil (LEO), which is rich in bioactive compounds such as citral, is well known for its potent antimicrobial and insect-repellent properties, making it highly attractive for textile applications [9–11]. In several nations, including China and Indonesia, this oil has also been proven to be effective in treating rashes, infections, and other health concerns [11]. LEO has been extensively studied for its therapeutic and antimicrobial properties and is considered an effective repellent against mosquitoes and houseflies. Its repellency is primarily attributed to its rich composition of bioactive constituents, particularly citral, which consists of geranial (trans-citral) and neral (cis-citral) as well as other compounds, such as geraniol and citronellol, all known for their potent antimicrobial and insect-repellent activities [12]. However, the effectiveness of LEO can vary depending on factors such as concentration, solvent type, and the specific plant species used for extraction [13]. Moreover, its volatility and susceptibility to environmental factors such as heat, light, and oxidation pose challenges for its direct application on textiles [14]. To overcome these limitations, microencapsulation techniques have been employed to stabilize essential oils and enable their controlled, long-lasting release, thereby enhancing both safety and functionality [15].

Microencapsulation is an advanced material-engineering strategy in which an active core, present as a solid, liquid, or gas, is entrapped within microscale shells fabricated from natural or synthetic polymer matrices [16]. These polymeric microcontainers, typically ranging from a few to several hundred micrometers in diameter, physically isolate the core from the external environment, enhance its physicochemical stability, and enable programmable release or targeted delivery in response to specific stimuli. Microencapsulation of essential oil has been achieved using different techniques and solutions [17, 18]. These techniques not only stabilize essential oils but also enable their controlled release, thereby extending their functional lifespan and maximizing the particles' shelf life, which ultimately enhances the quality of the final products. Among various microencapsulation strategies, emulsion-based systems, particularly those utilizing interfacial polymerization or particle-stabilized emulsions (Pickering emulsions), have shown enhanced stability and encapsulation efficiency. These systems confine shell formation at the oil–water interface, offering improved control over release and retention of volatile compounds such as essential oils [19]. The use of chitosan and gum Arabic as wall materials in microcapsule preparation offers advantages, such as biocompatibility, film-forming ability, and antibacterial activity [20]. In particular, microcapsules prepared via complex coacervation of gelatine with gum Arabic form thin, elastic solid walls ranging from 10 to 200 µm, and effectively encapsulate essential oils for pressure-triggered release [20].

The functionalization of cotton–polyester fabrics using microencapsulated essential oils offers an appealing route to combine textile comfort with bioactive properties. Such finishes have been shown to provide antimicrobial protection, insect repellence, and aromatherapeutic benefits, which are highly desirable for healthcare, home, and activewear applications [21–23]. Over the past decade, numerous studies have investigated the use of microencapsulated LEO on textiles, primarily for its mosquito-repellent activity. These formulations, often utilizing biopolymer wall materials, such as chitosan or gum Arabic, protect volatile compounds from rapid degradation and enable controlled release during wear. However, despite the established efficacy of LEO in laboratory conditions, many previous studies have lacked a holistic evaluation of multifunctionality, fabric comfort, and washing durability, particularly on blended fabrics such as cotton–polyester. Building upon these principles, this study focuses on the development and evaluation of multifunctional finishing textiles treated with LEO microcapsules. The key objectives include assessing mosquito-repellent performance across multiple washing cycles, quantifying antibacterial activity, evaluating aroma retention over time, and characterizing changes in surface morphology and comfort-related properties. By bridging the gap between lab-scale proof-of-concept and durability of the fabrics, this study contributes to the development of sustainable, functional fabrics for real-world applications.

2 Materials and Methods

2.1 Experimental Materials

The primary material (core material) used for the microcapsules in this study was LEO, a completely pure and certified organic, obtained from The Element Sdn Bhd. The wall materials used in this study were chitosan and gum

Arabic, which were obtained from Merck Sdn Bhd. Agents. Sodium tripolyphosphate (STPP), purchased from Merck Sdn Bhd, was used as the cross-linking agent, and Tween 20 as the emulsifier. All the reagents and compounds were used exactly as supplied, requiring no additional purification. For coating the LEO microcapsules onto the fabric, acrylic binder was used as the binding agent. The cotton–polyester fabrics were supplied by the Dyeing and Finishing Technology Workshop at Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Campus.

2.2 Preparation of LEO Microcapsules

This study used a complex coacervation method to produce LEO microcapsules (Fig. 1), as described in the study by Johan et al. [24]. First, the biopolymer solutions were prepared separately. Chitosan was dissolved in 0.1N acetic acid and left under magnetic stirring overnight to ensure complete dissolution. Gum Arabic solution was prepared by dissolving it in deionized water with continuous magnetic stirring at 45 ºC for 2 h. LEO was then added to the polymer solution, followed by the addition of Tween 20 under stirring at 8000 rpm for 10 min. The pH of the mixture was adjusted to 3.5, and the mixture was stirred for 30 min at 450 rpm. The temperature was then reduced to 5ºC with the aid of ice bath. Finally, the cross-linking agent, 2 ml of STPP (10% v/v), was added to the solution and kept under stirring at a constant temperature (5 ºC) for 3 h. The resulting microcapsules were stored in suspension for further analysis.

2.3 Application of Microcapsules onto Cotton–Polyester Fabric

LEO microcapsule dispersions were prepared at varying concentrations of 5, 10 and 15%. For each solution, 2 g/L of acrylic binder was added. The mixtures were stirred for 10 min using homogenizer (OMNI Macro Es, USA) at 5000 rpm. The prepared LEO microcapsule dispersions were then applied to the fabric using the pad-dry-cure method according to the above concentrations.

Cotton–polyester fabrics were immersed in the microencapsulated solutions prepared in the previous section for 5 min and then squeezed by padding to achieve a wet pick-up percentage of 70%. The percentage of wet pick-up was calculated as Eq. (1). The padded treated fabrics were dried at 100 °C for 3 min and cured at 95 °C for 2 min:

$$Wetpickup(\%) = \frac{Wafter - Wbefore}{Wbefore} x100 \tag{1}$$

where W_{before} is the mass of the dry fabric sample and W_{after} is the mass of the wet fabric sample after padding.

2.4 Microcapsule Characterizations

The particle size of LEO microcapsules was observed using advanced optical microscope operating in transmission light mode and equipped with Olympus Stream Essentials imaging software at 20 × magnification. The microcapsule solutions were mounted on a clean glass slide and covered with a cover slip. A total of 130 particle images from a single droplet LEO microcapsule were randomly selected. The diameter of each particle was recorded before calculating the mean particle diameter. The measurements were performed in triplicate. The surface morphology of the treated and untreated samples was investigated using scanning electron microscope (SEM) from COXEM, Korea. The specimen was fixed on specimen stub with double-sided adhesive tape and coated with sputtered gold.

2.5 Washing Durability

The washing durability of the treated sample was evaluated following the ISO 6330:2021 standard test protocol

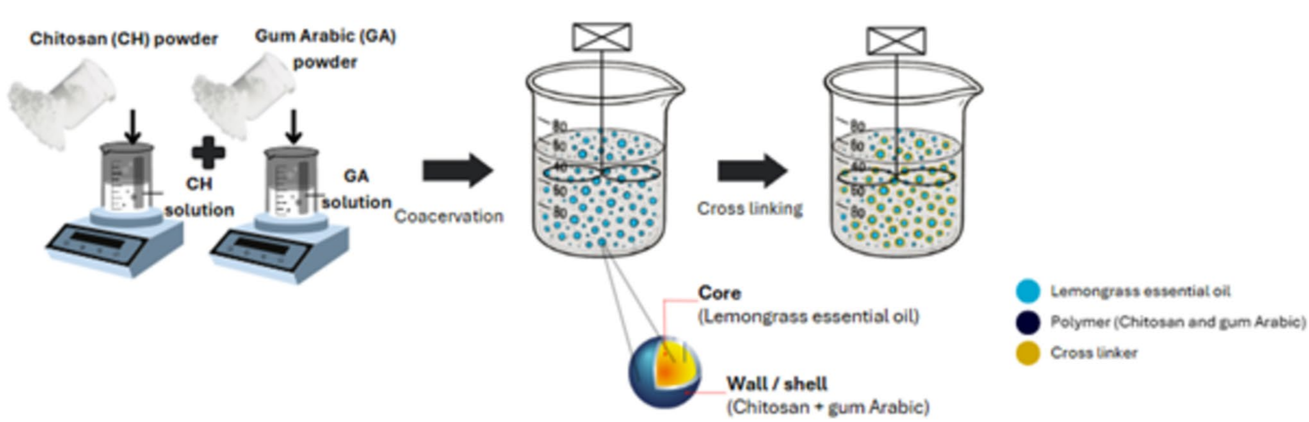


Fig. 1 Experimental procedure for the preparation of LEO microcapsule solution

using top-loading washing machine. As per the standard, 20 ± 1 g of IEC 'A' non-phosphate reference detergent was used. The sample was subjected to 10, 20, and 30 washing cycles.

2.6 Mosquito-Repellent Efficacy Test

The mosquito-repellent efficacy was evaluated using the arm-in-cage test method [25]. Aedes mosquitoes were obtained from Universiti Putra Malaysia (UPM) in Kuala Lumpur, Malaysia. A total of 30 female Aedes mosquitoes, aged between 7 and 10 days, were placed inside the screened cage measuring 30 cm (width) × 30 cm (height) × 30 cm (length), with two circular openings fitted with cloth sleeves. The mosquitoes were maintained at a temperature of 27 ± 2 °C under 12 h light:12 h dark photoperiod and were fed 10% sugar solution before being starved for 24 h before testing.

The laboratory repellency test followed the World Health Organization (2009) guidelines for efficacy testing of mosquito repellents on human skin, along with the Malaysian Standard Method (MS 1497:2000). Before the test, one forearm of the volunteer was covered with the treated fabric, while the other forearm was covered with untreated fabric. Gloves were worn to cover the rest of the hands. Then, the volunteer placed both hands inside the screened cage, as demonstrated in Fig. 2. The number of mosquito landings was manually recorded every 1-min intervals over 5-min observation period. The efficacy of the mosquito-repellent coating was determined using the following formula (Eq. 2):

$$Mosquitorepellentefficacyprotection(\%) = \frac{(C-T)}{C}x \tag{2}$$

where C is the total number of mosquitoes that land or bite on the untreated fabric, and T is the total number of mosquitoes that land and/or bite on the treated fabric.

2.7 Anti-bacterial Test

The antibacterial activity test was carried out using the method described by Julaeha et al. [26], following the Kirby–Bauer disk diffusion technique based on the SNI ISO 105-C06:2010 standard. The bacteria chosen for this study were common skin bacteria, namely, gram-positive *Staphylococcus epidermidis* (ATCC 11228) and gram-negative *Escherichia coli* (ATCC 11229). Each bacterial strain was first grown overnight in a disinfected saline solution at 10^5 CFU mL. A 500 µL bacterial suspension was then spread evenly onto nutrient agar plates using glass hockey stick. Disk papers (1 × 1 cm) were immersed in LEO microcapsule solutions of varying concentrations (5, 10 and 15%) and placed onto the agar. For uncoated samples, the disk papers were directly placed onto the agar. The process was repeated three times for each concentration. The plates were incubated at 37 °C for 24 h, and the antimicrobial activity was assessed by measuring the diameter of the inhibition zones (in mm).

2.8 Sensory Evaluation Test

The use of human assessors in sensory evaluation for textile aroma detection is feasible, since aroma is recognized by the sense of smell. The scientific field of sensory evaluation measures, analyzes, and interprets responses to the qualities of products as they are experienced by the senses of touch, hearing, taste, smell, and sight. Sensory evaluation is more commonly used in textile testing to assess tactile (such as fabric handle qualities) or visual (such as color and wrinkles) perceptions. In this study, the process involved treating the fabric with 2.5% non-ionic detergent at material-to-liquid

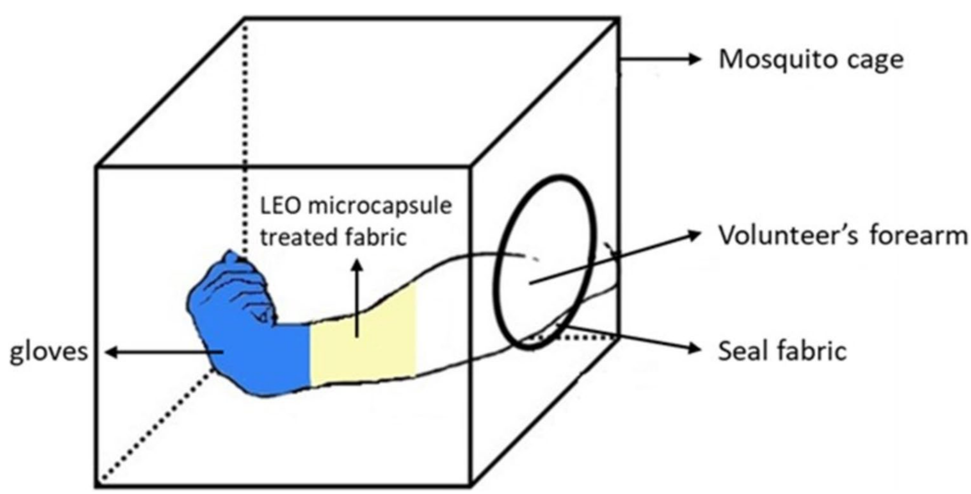


Fig. 2 Arm-in-cage test procedure

ratio of 1:30 for 10 min at 50 °C. After washing, the samples were rinsed with distilled water, squeezed, and dried in the oven at 60 °C for 2 min. Subjective assessment was then carried out to evaluate the fragrance retention of the LEO microcapsule-treated fabric. This method was adopted from Gogoi et al. [27].

The treated samples were stored in airtight polyethene bags and conditioned at 25 °C with 65% relative humidity for 24 h before evaluation. This sensory test was conducted to establish aroma retention, employing a group of assessors. The assessment was conducted blindly with five assessors, ensuring that sample details were not disclosed. Sensory evaluations were performed at different time intervals (1-, 15-, and 30-day post-treatment) to assess the longevity of the fragrance.

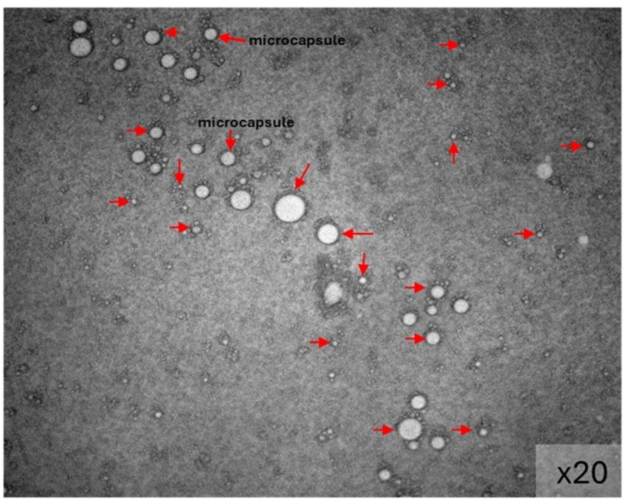


Fig. 3 Optical microscopic images of LEO microcapsules (20 × magnification)

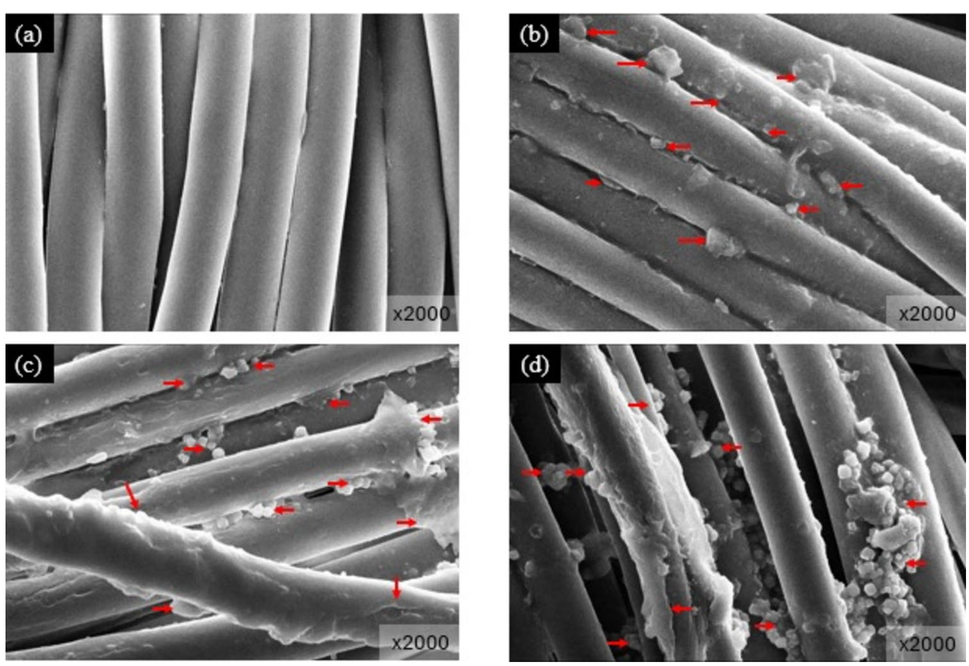
3 Results and Discussion

3.1 Morphological Assessment of LEO Microcapsules and Treated Fabrics

The morphological structures of the LEO microcapsules were observed, and it was found that the microcapsules were successfully enclosed and encapsulated as spherical particles, as shown in Fig. 3. However, their sizes varied, ranging from 2 to 50 µm. Jalali et al. [28] stated that smaller particle sizes offer a smoother fabric feel and improved adherence to textile fibers without reducing the fabric's comfort or texture. Microcapsules with a larger particle diameter are less likely to feel harsh on the skin [28]. The release rate of essential oil was influenced by the size of the microcapsules, where smaller microcapsules may enable a more controlled and prolonged release, thereby improving the longevity of the functional properties of the fabric.

Figure 4a shows the morphology of the untreated fabric, while Figs. 4b–d shows the morphology of the treated fabric with 2000 × magnification. The microcapsules were visibly distributed along the fabric fibers, with an increased concentration observed as the LEO microcapsule percentage rose from 5% to 15%. The images also confirmed that the adhesion between the textile fiber and microcapsules was

Fig. 4 SEM images of LEO microcapsules coated on cotton–polyester fabric at 2,000 × magnification: (**a**) untreated cotton–polyester fabric, (**b**) 5, (**c**) 10 and (**d**) 15%. Microcapsules attached to the fibers in the fabric are indicated by the marked arrows



effective and that the microcapsules were individually distributed without excessive agglomeration. The images in this study align with the findings in other studies [29–31]. The surface morphology of the microcapsules appeared soft and smooth. On the fiber surfaces, smaller microcapsules were also visible, suggesting that the microcapsules had moderate particle sizes and were suitable for fabric finishing.

3.2 Mosquito-Repellent Efficacy Test

Four different samples, including a control sample (untreated fabric) and fabrics treated with 5, 10 and 15% LEO microcapsules, were studied. Figure 5 presents a clear visual comparison of mosquito landing counts between untreated and treated fabrics before washing to highlight the initial treatment effect. As shown in Fig. 5, the untreated fabric recorded the highest number of mosquito landings, whereas the treated fabrics recorded fewer landings. This indicated that LEO possessed effective mosquito-repellent properties, as the number of mosquito landings reduced with increasing microcapsule concentration (%).

The effect of washing on mosquito repellence efficacy is presented in Table 1 as percentage protection, calculated from the mean number of mosquito landings (before and after washing) at various microcapsule concentrations. This approach avoided duplication of data shown in Fig. 5, which focused solely on the initial untreated–treated comparison. At 5 and 10% concentrations, the mosquito repellence efficacy reached 76.04 ± 3.34% and 82.40 ± 4.22%, respectively. The highest concentration (15%) provided 88.39 ± 2.24% protection before washing. However, after 30 washing cycles, the repellence efficacy decreased to 52.33 ± 4.35%, 52.29 ± 6.78% and 59.26 ± 8.72% for the 5, 10 and 15% LEO microcapsule concentrations, respectively. The fewest mosquito landings were recorded on the 15% microencapsulated treated fabric without washing, although the repellent activity decreased slightly after 10, 20, and 30 washing cycles. This reduction could be explained by the surface-active substances that are released from the fabric surface during the washing process [30]. These results indicated that the microcapsules retained their mosquito-repelling properties even after multiple wash cycles. The presence of citral in the LEO contributed to the fabric's effectiveness against Aedes aegypti mosquitoes. The findings also align with previous

Table 1 Mosquito-repellent activity of treated fabric (5%, 10% and 15%) after several washing cycles

No	Microcapsule concentration	No. of washings	Mosquito repellence efficacy protection percentage (%)
1	5	0	76.04 ± 3.34
		10	66.57 ± 3.36
		20	61.21 ± 3.42
		30	52.33 ± 4.35
2	10	0	82.40 ± 4.22
		10	67.20 ± 1.24
		20	64.83 ± 5.15
		30	52.29 ± 6.78
3	15	0	88.39 ± 2.24
		10	82.22 ± 5.04
		20	65.67 ± 3.65
		30	59.26 ± 8.72

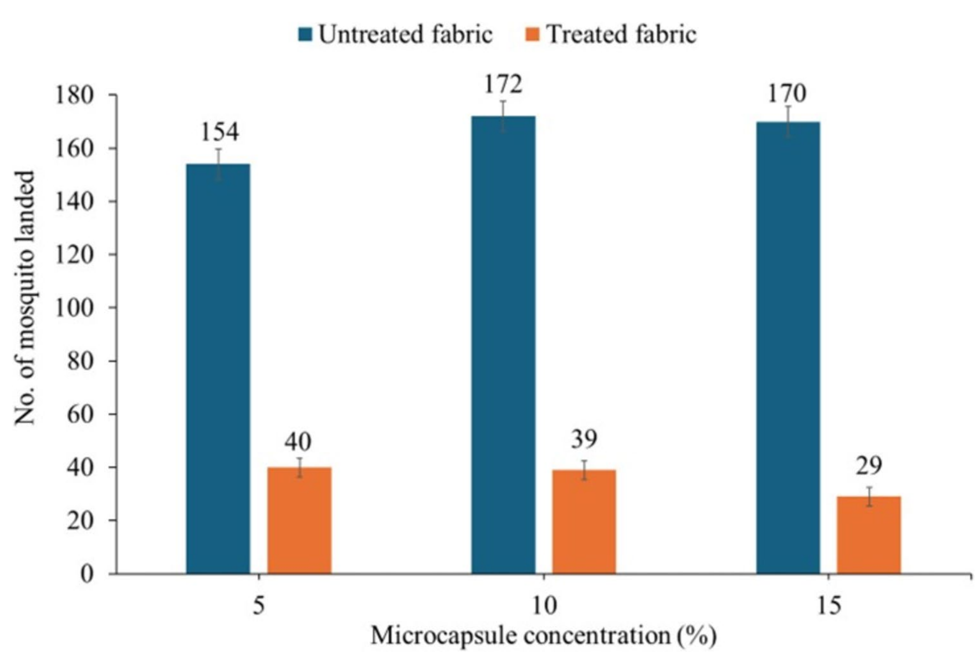


Fig. 5 Number of mosquito landings on untreated and treated fabrics (without washing)

Table 2 ANOVA results for mosquito-repellent efficacy

Source	DF	Adj SS	Adj MS	*F* value	*P* value
No. of washing	3	4746.7	1582.22	57.57	0.000*
Microcapsule concentration (%)	2	401.4	200.70	7.30	0.003*
No. of washings*microcapsule concentration (%)	6	823.1	137.18	4.99	0.002*
Error	24	659.6	27.48		
Total	35	6630.8			

Df degree of freedom, *SS* sum of squares, *MS* mean square, *F F* test, *p p* value

*The value is less than 0.05, implying significant factor effect as mentioned above

studies using peppermint oil, which demonstrated over 90% mosquito repellence in cage tests [32].

Table 2 presents the ANOVA results for mosquito-repellent efficacy based on various sample types, numbers of washing cycles, and microcapsule concentrations. The analysis indicated that the concentration of microcapsules and the number of washing cycles had a significant influence on repellent efficacy. Significant interactions between these factors were observed, as presented by *p* values less than 0.05. The residual distribution showed low variability, with R^2 value of 90%, supporting the reliability of the experimental data. Among the variables, the number of washing cycles had the greatest impact, as indicated by the highest *F* value and the largest sum of squares, suggesting that repeated washing substantially diminished the efficacy of the microcapsules. Microcapsule concentration also had a notable effect, with higher concentrations enhancing repellent performance. Furthermore, the interaction between washing cycles and microcapsule concentration was statistically significant, indicating that the influence of washing on efficacy depended on the concentration level of the microcapsules. The ANOVA analysis highlighted the significance of both factors in influencing the durability and mosquito-repellent efficacy of the treated fabrics, with washing cycles exerting the most substantial impact, followed by microcapsule concentration and their interaction.

3.3 Antibacterial Test

The antibacterial activity test was conducted using two bacterial species: (a) *Staphylococcus epidermidis* (gram-positive) and (b) *Escherichia coli* (gram-negative). Table 3 presents the inhibition zone (cm) of bacterial growth using different LEO microcapsule concentrations. The results demonstrated that the size of the inhibition zones increased with higher concentrations of LEO microcapsules, particularly at 15%, indicating enhanced antimicrobial effectiveness

Table 3 Inhibition zones of bacterial growth using different LEO microcapsule concentrations

Microcapsule concentration (%)	Zone of inhibition (cm) against bacteria	
	Staphylococcus epidermidis (gram-positive)	Escherichia coli (gram-negative)
5	2.00 ± 0.4	1.67 ± 0.6
10	1.30 ± 0.4	1.57 ± 0.6
15	2.83 ± 0.3	2.80 ± 0.1

with increased concentration. This finding aligns with existing literature, which suggests that higher concentrations of this oil enhance the antibacterial activity of fabrics, typically leading to more significant inhibitory effects on microbial growth [33]. The increased inhibition zones in this study further supported the commonly observed dose–response relationship in antimicrobial research, where higher agent concentrations of these oils resulted in more pronounced microbial inhibition.

At lower concentration (5%), the fabrics showed moderate antibacterial activity, with inhibition zones of 2.0 cm for *S. epidermidis* (gram-positive) and 1.67 cm for *E. coli* (gram-negative). Interestingly, at the 10% concentration, the inhibition zones decreased to 1.30 and 1.57 cm for *S. epidermidis* and *E. coli*, respectively, suggesting a potential dip in antibacterial activity. However, at the highest concentration (15%), the fabrics exhibited the largest inhibition zones, 2.83 cm for *S. epidermidis* and 2.8 cm for *E. coli*, indicating a significant increase in antibacterial effectiveness.

The data suggested that the antibacterial activity was concentration-dependent, with higher concentrations (15%) being the most effective. This concentration dependency was likely due to higher amounts of LEO microcapsules releasing more antibacterial agents, enhancing their ability to inhibit bacterial growth. This finding aligns with the study by Said et al. [34], which reported that higher concentrations of LEO microcapsules result in a greater release of active compounds, thereby enhancing antibacterial efficacy. This is significant as the concentration of these agents directly correlates with their effectiveness in inhibiting bacterial growth.

In addition, the larger inhibition zones for *S. epidermidis* compared to *E. coli* at lower concentrations implied that gram-positive bacteria were more susceptible to LEO microcapsules than gram-negative bacteria. This could be attributed to structural differences in bacterial cell walls, as gram-negative bacteria possess an outer membrane that offers additional protection against antibacterial agents. This observation is consistent with findings by Bruslind [35], who also noted this characteristic. The slight reduction in inhibition zones at the 10% concentration may have resulted from factors such as uneven coating, as reported in previous study by Kamaruzzaman et al. [36].

Furthermore, Akter et al. [15] reported that polymeric carriers such as chitosan offer dual functionality, serving not only as structural matrices but also as antibacterial agents due to their positive surface charge, which disrupts bacterial membranes via electrostatic interactions. The inherent antimicrobial activity of chitosan enhances the efficacy of essential oil-loaded systems. Embedding essential oils in polymeric systems has also been shown to prolong their biocidal activity, ensuring sustained antimicrobial protection [15]. These characteristics are particularly important for textile applications requiring both efficacy and durability over time.

Overall, the findings highlighted the potential of 15% LEO microcapsules as a highly effective antibacterial treatment for textiles, particularly for applications requiring strong antimicrobial activity.

3.4 Sensory Evaluation Test

The sensory test results shown in Table 4 revealed the aroma retention across varying concentrations of LEO microcapsules over time. Aroma intensity was measured on a scale of 1–4, where 1 indicated a mild aroma, 2 indicated moderate, 3 denoted strong, and 4 represented very strong. Initially, after 1 day, samples with 15% LEO microcapsule concentrations (3.4) exhibited the highest aroma values, indicating superior initial aroma. In contrast, lower concentration samples (5%) showed relatively weaker initial aroma values. Over time, particularly after 30 days, all samples experienced significant reduction in aroma. Notably, the aroma intensity of samples treated with 5 and 10% LEO microcapsules dropped to 1.2–1.3, suggesting that prolonged storage reduced aroma intensity, with the rate of decline influenced by both the concentration of LEO microcapsules and the binder formulation. These findings align with previous studies, which demonstrated that higher microcapsule concentrations enhance initial aroma retention initially but may be less effective at sustaining it over extended periods [31, 32].

In addition to sensory evaluation tests, assessments of hand feel were conducted through tactile inspection. Tactile sensory evaluations revealed that LEO microcapsule and binder concentrations had a measurable effect on the comfort-related properties of the treated fabrics. On the first day, all concentrations exhibited smooth textures with mean tactile ratings of approximately 3.0 on five-point scale, indicating acceptable softness for wearer comfort. However, after 15 days of storage, the ratings decreased by 0.6–1.0 points depending on concentration, reflecting a gradual shift toward rougher surfaces. This decline coincided with reduced aroma stability, suggesting a relationship between surface texture degradation and volatile loss. Such changes were likely to influence both the perceived comfort and sensory appeal of the fabric in practical use. Similar observations are reported by Gogoi et al. [27], who noted that higher microcapsule concentrations preserved softness and sustained aroma retention over time, contributing to better user experience.

Table 4 Subjective assessment of aroma retention after storage

Particular	Microcapsule concentration (%)		
	5	10	15
After 1 day	3.2	3.0	3.4
After 15 days	2.0	3.0	2.4
After 30 days	1.2	1.3	1.8
Tactile sensory evaluation after 1 day	3.0	3.0	3.0
Tactile sensory evaluation after 15 days	2.0	2.0	3.6
Tactile sensory evaluation after 30 days	3.0	3.0	3.0

While this study emphasizes the eco-friendly potential of LEO as a bio-based functional agent, it is also important to contextualize this work within the broader framework of sustainable material sourcing and circular textile innovation. Lemongrass (*Cymbopogon citratus*) is a renewable agricultural resource, widely cultivated in tropical regions, and its extraction process has lower environmental impact compared to synthetic repellents such as DEET. Utilizing such plant-derived essential oils aligns with circular economy principles by encouraging biodegradable, non-toxic, and renewable inputs. Furthermore, the biopolymer shell materials used in microencapsulation, such as gum Arabic and gelatine, are themselves biodegradable and naturally derived, further reinforcing the sustainability of the finishing system.

This approach also reduces dependency on petroleum-based finishes while adding value to agricultural by-products, which are often underutilized. As highlighted in recent literature, sustainable finishing technologies that integrate natural ingredients, low-energy processes, and extended product lifespans are central to the textile industry's transition toward circularity [37]. Such approaches align with current industry efforts in sustainable material sourcing and valorization of agro-waste for high-value textile applications, positioning the developed multifunctional fabric as both high-performance and environmentally responsible product. By demonstrating the durable performance of LEO-based microencapsulated multifunctional finishes, this study contributes to ongoing efforts in designing textiles that are both functional and environmentally responsible, suitable for applications in health, wellness, and sustainable fashion.

4 Conclusion

The scientific results of this study confirmed the successful synthesis of LEO microcapsules and their application to cotton–polyester fabric. The microcapsules were spherical in shape, as verified by both the optical microscope and SEM. They were applied (treated) to the fabric using the pad-dry-cure process, after which their mosquito-repellent efficacy and washing durability were evaluated. The finished fabric demonstrated effective mosquito repellent against the Aedes aegypti species, which can be attributed to the presence of citral in LEO. Even after 30 vigorous washing cycles, the treated fabric retained potent mosquito-repellent properties, demonstrating the durability of the microcapsule finish. In addition, the LEO microcapsules exhibited a clear inhibitory effect on bacterial growth for both types of microbes, demonstrating their ability to suppress microbial proliferation. The inhibition zone size increased with higher concentrations of LEO microcapsules, with the largest zone observed at 15%, measuring 2.8 cm. Ultimately, the aroma of the treated fabrics was slightly affected by the application of LEO microcapsules. Aroma retention tests revealed that higher concentrations provided a stronger initial fragrance (rating 3.4/5.0); however, the scent gradually diminished over time (1.8/5.0), indicating potential instability in encapsulation. Thus, this study provides a novel method for creating a durable mosquito-repellent coating for eco-friendly functional textiles. Such treatments have promising potential in application areas requiring prolonged protection and hygiene, including healthcare uniforms, sportswear, outdoor apparel, and military or work uniforms. Future research should explore the performance of the treatment not only under washing conditions but also when exposed to environmental factors, such as sunlight, humidity, perspiration, and abrasion during actual wear. This will provide valuable insights for both the scientific community and the textile industry, potentially leading to more durable and effective multifunctional textiles.

Author Contributions Nur Ain Arina Johan: methodology, formal analysis, investigation, writing—original draft, writing—review and editing, and project administration. Hannan Hamimi Hasmadi: writing—editing and project administration. Khatheline Shantie Peter: experimental work, writing—review and editing, and project administration. Siti Hana Nasir: writing—review and editing, visualization, supervision, project administration, and conceptualization. Helmy Mustafa El Bakri: funding acquisition, validation, formal analysis, and supervision. Norashiqin Misni: supervision and project administration.

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Data Availability Data will be made available on request.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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