Design & Development of a Mosquito-Repellent Fabric with Enhanced Wash Durability

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Keywords—Mosquito repellent textile, Electrospraying, Citronella oil microcapsules, Wash durability

I. INTRODUCTION

The development of mosquito-repellent textiles has emerged as a significant innovation in the textile industry. This novel approach involves applying a mosquito-repelling agent to textile materials, effectively transforming them into protective barriers against mosquitoes. In reviewing existing research on mosquito-repellent agents and their applications in textiles, it is evident that while many studies focus on whether the materials possess mosquito-repellent properties, few addressed the durability of these solutions, particularly concerning wash fastness. Thus, a significant research gap has been identified in the wash durability of developed mosquito-repellent textiles, especially in utilizing natural agents. These agents tend to lose their effectiveness substantially after washing. To address this problem, the study proposes a comprehensive investigation aimed at enhancing the wash durability of natural mosquito-repellent agent-based textiles by incorporating microcapsules with co-encapsulated materials.

II. LITERATURE REVIEW

Throughout the world, mosquitoes represent one of the biggest risks to both human and animal health [1]. More than 700,000 people die from vector-borne illnesses each year, the most common being dengue and malaria, which account for more than 17% of infectious disease case [2]. The widespread transmission of vector-borne diseases poses a significant threat to public health, making it critical to implement effective control measures and prioritize personal protection to reduce the risk of infection and prevent further fatalities. Textile-based solutions are particularly important, as textiles are considered one of the elements which are worn closer to the human body, thus ensuring protection from textiles has appeared to be providing a significant impact on human life. Both natural and synthetic agents can be incorporated into mosquito-repellent textiles. DEET, Permethrin, Icaridin, Malathion, and IR3535 are widely used synthetic repellent agents. However, these synthetic mosquito repellent agents possess several health risks including skin and eye irritation, and alterations in the immune system, raising concerns about their long-term safety and impact on human health [3]. Natural mosquito repellent agents are often preferred over synthetic alternatives as they offer ecofriendly and biodegradable solutions with minimal or no adverse effects on humans. Plants like Cinnamomum, Citronella, Citrus, Eucalyptus, Neem, Clove, Turmeric, Rosemary, Zingiber possess insecticidal properties, and their essential oils and extracts have been traditionally used for generations as personal protection against mosquitoes [4]. The repellent properties of citronella have been well-documented in various studies, identifying it as an essential oil extracted from the stems and leaves of different lemongrass species (Cymbopogon spp.) [5].

Based on Kongkaew et al. [6], a systematic review of complete repellency from the 25% citronella oil and 5% vanillin combination lasted for up to 6 hours. A similar result was observed with 40% citronella oil alone. Due to its extended protection when combined with vanillin, citronella-based products could serve as an alternative to DEET, particularly for individuals who experience adverse effects or allergic reactions to DEET [6].

To translate this potential into durable textile applications, the present study employs microencapsulation as a strategic approach. Ramya and Maheshwari [7] reported the preparation of sodium alginate microcapsules loaded with andrographolide via ionic gelation, which were subsequently applied to bamboo/cotton fabric using the exhaustion method. The finished fabrics achieved 94% mosquito repellency, only slightly lower than the 96% observed in directly finished fabrics. Building on this, the current work explores citronella essential oil as the primary active ingredient, co-encapsulated with vanillin, to investigate the synergistic effect and evaluate improvements in wash durability.

III. MATERIALS AND METHODS

A. Materials

94% Cotton, 6% Spandex 1x1 Rib structured fabric was obtained from Teejay Lanka (Sri Lanka). This composition was specifically chosen to balance the desired textile properties, providing the softness, breathability, and moisture-

https://doi.org/10.31705/TERS2025.3

wicking capability of the cotton content with the essential stretchability provided by the minor spandex component. Citronella oil served as the main active agent, and vanillin solution was incorporated as a secondary core material. Sodium alginate was used as wall material, with $CaCl_2$ serving as the crosslinking agent. Tween 80 was included as a surfactant. Citric acid was used as the binding agent.

B. Preparation of Citronella Oil loaded microcapsules

The feed solution was prepared by dissolving a 2.544% (w/v) sodium alginate in distilled water and stirred until complete dissolution. 0.3 ml of Tween 80 was added to the prepared sodium alginate solution. Subsequently, citronella oil was added dropwise to the sodium alginate solution, maintaining a core to wall ratio of 1:3 and stirred for 2 hours. The solution was loaded into a 10 mL syringe with a 21G needle for electrospraying. The crosslinking solution was prepared by dissolving 10.529% (w/v) $CaCl_2$ in distilled water and placed in a Petri dish on the collector stage. Electrospraying was performed at 10 kV with various feed flow rates (0.5, 0.3, 0.2, 0.1, 0.08, and 0.05 mL/min) to determine optimal microcapsule formation. The resulting microcapsules were collected in the $CaCl_2$ solution, then washed, filtered, and dried.

C. Preparation of Citronella Oil–Vanillin Co-Encapsulated microcapsules

This followed the general procedure outlined in Section B with the following modification to the spraying feed solution. After the incorporation of citronella oil, vanillin solution was added dropwise to the sodium alginate solution, maintaining an overall core-to-wall ratio of 1:3. The electrospraying process was performed at flow rate of 0.05 mL/min. The obtained microcapsules were collected in $CaCl_2$ solution, followed by washing, filtration, and drying.

D. Characterization of Microcapsules

The size and morphology of microcapsules were determined by Optical microscopy and SEM. FTIR spectroscopy was performed to confirm the successful synthesis and encapsulation of citronella oil and vanillin within the microcapsules.

E. Release Study

The release behavior of the microcapsules was first evaluated by determining the minimum force required for rupture, followed by recording the initial weight (W_0) and measuring the weight of the released contents at 5-minute intervals over 30 minutes, with the final weight (W_{30}) recorded at the end. The cumulative release percentage was determined using the following equation:

$$Release\,\% = \frac{W_0 - W3_0}{W_0} \times 100 \qquad (1)$$

F. Textile Treatment

Greige 94% cotton and 6% spandex fabric was scoured to enhance binding affinity and was cut into 5 cm × 5 cm swatches. Following that a 10% citric acid binder was applied to the fabric to facilitate microcapsule attachment via the exhaustion method and dried for 24h.

G. Mosquito Repellency Test and Washing Assessment

The mosquito repellency was evaluated using the excito chamber test, conducted in accordance with the modified WHO method [8]. Twenty-five adult female mosquitoes, aged 4 to 7 days, were taken for the tests. The excito chamber was constructed with two opposite sides covered using polythene material for observation. After a 3-minute acclimatization period, the number of mosquitoes escaping was recorded manually at 1-minute intervals over a 5-minute observation period. The following samples were evaluated:

S0 – Untreated fabric sample (control sample)

S1 – Fabric treated with Citronella Oil loaded microcapsules

S2 – Fabric treated with microcapsules co-encapsulating Citronella Oil and Vanillin.

The percentage of mosquito repellency was calculated using the specific formula given below [9].

$$Mosquito\ Repellency\ \% = \frac{(No\ of\ mosquitoes\ escaped + No\ of\ mosquitoes\ dead)}{No\ of\ mosquitoes\ exposed} \times 100 \qquad (2)$$

Samples S1, and S2 were evaluated both before and after 5, 10, 20, and 30 wash cycles. Wash durability was assessed following the ISO 6330, 5A method.

IV. Results and discussion

A. Investigation of electrospraying parameter effects on microcapsules formation

In the preparation of both type of microcapsules, it was found that the flow rate had a negative effect on the particle diameter. As the flow rate decreased, microcapsule sizes also reduced, which concurrently contributed to improved capsule size uniformity and spherical shape. It was found that the flowrate of 0.05 mL/min was optimal for producing uniform microcapsules. The optical microscopic image presented in Fig. 1 shows the microcapsules formed at 0.05 mL/min flowrate.

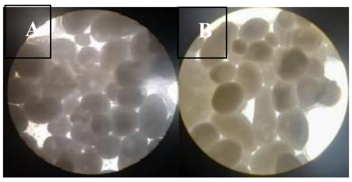

Fig. 1. Optical images of Microcapsules with (A): Citronella Oil (B): Citronella Oil and Vanillin

B. SEM and FTIR Analysis

The SEM image of microcapsules shown in Fig. 2 reveal that the microcapsule formulations exhibited a tendency for agglomeration. Microcapsules prepared at a flow rate of 0.05 mL/min exhibited a mean diameter of 241.7 µm. The FTIR results confirmed with their respective peaks indicating the successful synthesis of materials during microcapsule formation.

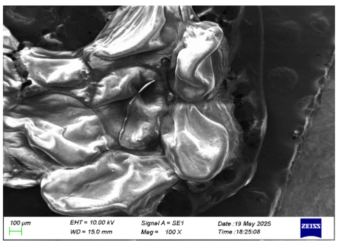

Fig. 2. SEM image of Microcapsules

C. Release Study

The core material release in this study was evaluated by measuring the amount of active agent released following the mechanical rupture of the capsule walls. Results from the release study indicated that the microcapsules began to release core material at a minimum applied weight of 20g. As presented in Table 1, the total release of the core material over a 30-minute period varied significantly depending on the microcapsule type. The results indicate that microcapsules co-encapsulating citronella oil and vanillin released a lower amount of core material compared to microcapsules loaded with citronella oil alone. This suggests that the incorporation of vanillin solution effectively reduced the release rate of citronella oil.

TABLE I: RELEASE % OF CRUSHED MICROCAPSULES

Microcapsule Type	Weight of capsules (g) at t=0 min	Weight of capsules (g) at t=30 min	Release % over 30 mins
Citronella Oil loaded microcapsules	0.0904	0.0348	61.5044
Citronella Oil and Vanillin co-encapsulated microcapsules	0.1209	0.0678	43.9206

D. Mosquito Repellency & Wash Durability

The mosquito repellency results indicated that the untreated control samples offered no protection against mosquitoes. In contrast, the microcapsule-treated fabric samples, particularly before washing, generated a significantly higher level of mosquito repellent activity compared to the subsequent washed samples.

Among the encapsulated samples, both the single-active (S1) and co-encapsulated (S2) treatments initially demonstrated high mosquito repellency, achieving 84% and 88% effectiveness, respectively. This initial repellency confirms the inherent activity of the released citronella oil and the synergistic effect of the vanillin solution. However, after 30 washing cycles, the repellency for S1 and S2 dropped sharply to 4% and 8%, respectively, highlighting the poor wash durability and limited long-term efficacy of the microcapsules.

Critically, the direct comparison between the two treatments reveals the significant impact of vanillin: Sample S2 consistently exhibited better repellent activity than Sample S1 confirming that the presence of vanillin substantially enhanced the mosquito repellent effect.

V. CONCLUSION

This study successfully demonstrated the development of mosquito-repellent fabrics via microencapsulation technique aimed at enhancing wash durability of natural repellent agents.

The key findings confirmed the effectiveness of the strategy: the co-encapsulation of the vanillin solution with the primary active agent, citronella oil, resulted in a slight but consistent improvement in mosquito repellency and measurably enhanced the wash durability compared to the citronella-only microcapsules. While this co-encapsulation approach partially addressed the major limitation of poor durability inherent to natural finishes, the overall long-term efficacy remains a challenge.

The results strongly suggest that the presence of the vanillin solution acts as an effective rate-retardation component, prolonging the release of the repellent and improving overall performance.

Future research will focus on strategic areas like developing more robust polymer wall materials and investigating higher-crosslinked systems to significantly prolong wash durability against environmental conditions, and optimizing the application method by evaluating different binders to firmly attach the microcapsules while analyzing the impact on the fabric's comfort properties such as hand feel and breathability.

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