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Progress in mosquito repellent textiles: factors, methods, and challenges

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Abstract

Mosquito-borne diseases such as malaria, dengue, chikungunya, and yellow fever pose a significant global health threat, with malaria alone causing hundreds of thousands of deaths annually. Climate change has exacerbated mosquito proliferation, necessitating innovative solutions to combat these diseases. Textiles engineered with mosquito-repellent characteristics have become a practical alternative to fight against vector-borne diseases. Not only synthetic chemicals, i.e., DEET, permethrin, etc, but also natural agents like essential oils or plant extract have been successfully applied onto fabrics through dyeing, printing, coating, grafting, and encapsulation. These techniques not only introduce the insect repellency but also embed multifunctional activity, e.g., UV protection, antimicrobial activity, etc. Although this domain of functional textiles has made notable progress, the research communities are still trying to find a more feasible and suitable approach, and at the same time, overcome the existing limitations in achieving long-term effectiveness, user comfort, and environmentally sustainable options. This review discusses the advancements mosquito repellent textiles by applying both natural and synthetic repellents, covering application methods, assessment criteria, and material selection. It offers insights for developing effective and diverse mosquito-repellent textiles. This study contributes a unique, in-depth analysis of this field, highlighting the opportunities and limitations of current strategies while enhancing understanding and guiding future research endeavours.

1. Introduction

Mosquitoes, known for transmitting deadly diseases, pose a significant threat to human life [1]. The increasing mosquito population globally has led to millions of deaths, with 438,000 individuals succumbing to malaria alone in 2015 [2]. Climate change has created environments that favor mosquito proliferation, facilitating the spread of diseases like malaria and dengue worldwide [3, 4]. To be precise, such cases tend to be prevalent in tropical and subtropical regions where weather conditions facilitate expansion of new territories [5]. In these areas, protection from blood-feeding arthropods, such as mosquitoes, becomes essential, particularly in rural areas, parks, forests, and other outdoor settings [6].

Diseases like dengue, malaria have become health concerns globally as they are evident to be life-threatening. Malaria, mostly by *Anopheles* a major cause of illness and death in almost 91 countries [7], and lacks effective vaccines [1]. In 2023, there is a report including 94% of malaria cases (246 million) and 95% of malaria

deaths (569000) by the WHO African Region [8]. Similarly, *Aedes aegypti* holds millions of cases of dengue, Zika, yellow fever, and chikungunya [9]. In 2023, dengue cases have been reported to have skyrocketed by 10 times from 500000 in 2000 to 5.2 million in 2019. These staggering numbers demonstrate the need to take necessary initiatives to prevent incidents and deaths [10].

The absence of vaccines or specific treatments makes mankind vulnerable while fighting against the risk of mosquito-borne diseases [11]. So, there are several preventive options indoors, like long-lasting insecticidal nets (LLINs) and WHO-recommended indoor residual spray (IRS) [12]. In an outdoor environment, exposed skin needs to be protected by repellents, which can be in creams, gels, and lotions [13]. In contrast, Nagender *et al* utilized *Thymus vulgaris* oil using microencapsulation [14]. However, the majority of them possess a certain level of toxicity and health risk, such as skin irritation, skin burning, neurotoxic, cardiotoxic, kidney disease, etc. Therefore, alternative solutions are pressing needs to avoid those side effects [6].

Researchers are actively exploring new insecticides and repellents to combat mosquito-borne illnesses [15]. Recent studies have focused on developing mosquito-repellent textiles to protect against diseases like malaria, dengue, Zika, chikungunya, and yellow fever [16]. While traditional products like lotions and creams offer some protection against mosquito bites, they often have limited efficacy and may harm the skin [2]. In contrast, mosquito-repellent textiles present a promising solution by covering larger areas of the body effectively [2, 17]. There, mosquito-repelling agents are incorporated into textiles in several ways, resulting in better protection and safety than direct application to the human skin. Mosquito repellents can be classified into two types such as chemical/synthetic repellents and natural repellents [18]. Evidently, synthetic agents perform better than natural agents in terms of longer-lasting protection. However, they cause a threat to the environment, human beings, animals, and aquatic species. Hence, natural repellents are being explored widely despite less durability [19].

Common synthetic repellents e.g. N, N-diethyl-meta-toluamide (DEET) [2, 20], picaridin [21], Permethrin [22, 23] etc are widely used, while natural options i.e., essential oil and extracts from citronella, lemon, eucalyptus etc [4, 24]. For instance, Mokhtari *et al* combined azo reactive dyes with DEET for this purpose [13]. In contrast, Nagender *et al* utilized *Thymus vulgaris* oil using microencapsulation [14]. However, in most of the cases, priority has been given to essential oils as an alternative to synthetic repellents [6].

A diverse range of active insect repellents with varying concentrations and durations of effectiveness are available in the market for embedding in textiles, or impregnating fabrics [3] in ways like novel dye synthesis [2, 16], microencapsulation [25–27], electrospinning [28, 29] and grafting [30]. For example, Ankit *et al* reported the synthesis of a novel cationic dye to impart mosquito repellency [16], where this yielded dye-fiber interaction to fulfil the durability criteria. Similarly, Ankit *et al* found a novel method of azoic dyeing with *Terminalia chebula* for the protection from mosquitoes [31]. Moreover, Geethadebi *et al* achieved a mosquito repellent feature on a blended fabric by microencapsulation of essential oil. In addition, Ashley *et al* utilized electrospinning to get durable insect repellency. Besides, Wen *et al* employed eugenol graft modification to impart multi-functionality along with mosquito repellent. These techniques are invaluable in the case of obtaining durable and long-lasting protection against mosquito bites [32].

These aforementioned repellents can be embedded on wearable textiles, upholster items [33], eave sealants [34] or long lasting net (LLN) [7, 35] in a various application methods such as dyeing [16, 36, 37], printing [2, 38], pad-dry-cure [17], spraying [27, 39], coating [38, 40, 41], immersion [3, 42] etc. Researchers also established a mathematical model for fabric construction and repellency evaluation [43, 44]. Gungordu Er, S. *et al* shows in how biosensor can help in Diabetics detection. The same way can be used for mosquitos' detection. Biosensors are proving to be highly useful in a variety of applications, including the detection of mosquitoes. The same technology that smart devices use to assess temperature, sweat, and heart rate can also be used to identify mosquitoes [45]. Another method can be Acoustics and Image-Based Detection which is a method to detect mosquitoes near the human body using image processing and deep learning machines. by putting in a textile-based sensor that can almost 'see' and 'hear' a mosquito. It can identify mosquitoes by vibrating, flashing, or sending a notification. Real-time Detection and Alerts are highly popular. By adding embedded sensors that can identify mosquitoes by their presence, it can be applied to curtains, bed nets, and clothes. When individuals are sleeping at night or in a location where mosquitoes are prevalent, its development can lessen the frequency of mosquito bites. And other options of using biosensor Integration with smart textiles and wearable technology: Breathable sophisticated textiles can now perform sensing duties without causing any pain. It can even be utilized in optical fibers, flexible sensors, conductive yarns, and textile electronics.

The pressure-spinning technique, specifically the modified nozzle-pressurized spinning (NPS) described in this research, offers a novel and economical approach for textile manufacturing. This method utilizes centrifugal force assisted by high-pressure nitrogen to extrude cellulose solutions through nozzles, forming fibers or ribbons without the need for high voltage or energy-intensive processes like electrospinning. The process is simple, efficient, and environmentally friendly, as it avoids hazardous chemicals and high energy consumption. Additionally, it allows for continuous production of small-structure fibers with controllable morphology by

adjusting parameters such as solution concentration, rotational speed, and pressure. This makes pressure-spinning a promising alternative for sustainable textile fabrication, especially when utilizing recycled bio-based materials like nanocellulose from agricultural waste, thus aligning with circular economy principles [46].

Unlike conventional fiber production techniques such as electrospinning, which rely heavily on high-voltage electric fields and often involve toxic solvents, pressure-spinning utilizes centrifugal forces and pressure to extrude polymer solutions into fibers. This process eliminates the need for high voltage, reducing energy consumption and safety risks. One of the key advantages of pressure-spinning is its high throughput capacity, allowing for the rapid and efficient production of fine polymeric fibers. This high efficiency can lead to lower production costs, especially when scaled up. Additionally, the process can use water-based or less toxic solutions, minimizing environmental impact and chemical waste—an essential factor in sustainable textile production. The recent development of battery-powered pressure-spinning devices further enhances its economic and environmental appeal by enabling off-grid operation, portability, and on-demand manufacturing. This portable approach reduces reliance on large infrastructure and grid energy, making textile production accessible in remote or resource-limited settings. Such flexibility can lead to cost savings and broaden the scope of textile manufacturing, including in medical, environmental, and small-scale artisanal applications [47]. In this study, conducted using the Scopus database, 151 papers were initially identified by searching for keywords ‘Mosquito AND Repellent’ OR ‘Mosquito AND Resistant’ AND ‘Textile*.’ After filtering out non-English language articles and focusing on the time frame from 2000 to 2025, the number of relevant papers reduced to 117. After identifying the relevant articles through the Scopus database search, this study thoroughly reviewed and categorized the available papers based on the predominant interests of researchers in the field of mosquito repellent textiles. The review process involved a detailed examination of the selected papers to categorize them according to the primary focus areas that garnered the most attention from researchers. The reviewed articles encompassed a wide range of topics, including methods of imparting mosquito repellent agents on textiles, assessing mosquito repellency, and exploring different textile materials for protection against mosquitoes.

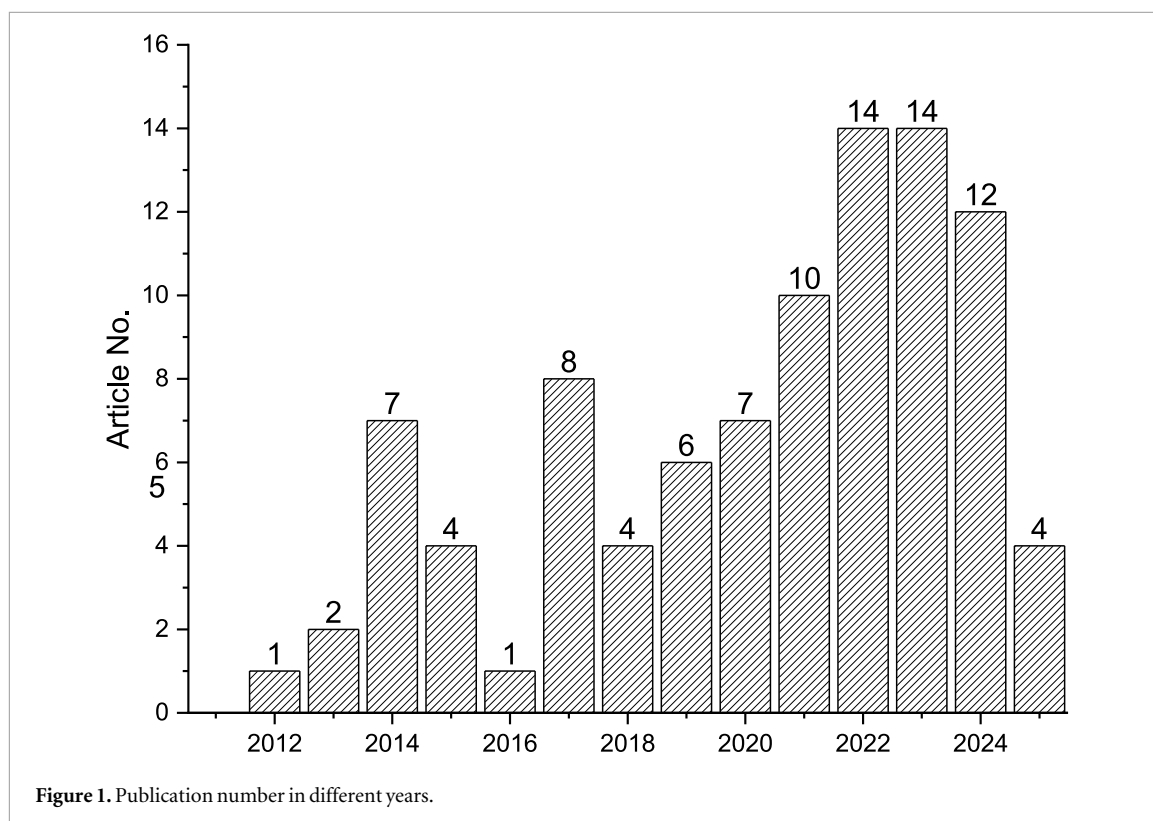
While previous research has primarily examined specific aspects like recent advancement and progress on microencapsulation of essential oils [48, 49], different methods and assessment procedures [50], insect repellency on cellulosic fabric [51, 52] only eco-friendly mosquito repellent textiles [52, 53], or different finishing applied against microbes, mites etc [54–56] this study uniquely synthesized a comprehensive analysis of mosquito-repellent textiles utilizing both natural and synthetic sources applied to a variety of textile materials. This review delved into the application methods, assessment criteria, and other relevant factors associated with mosquito-repellent textiles. By consolidating and categorizing the works of multiple authors in this domain, the study aimed to provide an in-depth exploration of the development, application methods, and evaluation criteria of mosquito-repellent textiles using a combination of natural and synthetic sources. The study asserts that to the best of the author’s knowledge, no work of such depth and breadth has been reported in this domain previously. This comprehensive review contributes valuable insights into the field of mosquito-repellent textiles by offering a holistic perspective for developing effective mosquito repellent textiles with diverse applications.

2. Works on mosquito repellent textiles

Numerous researchers in the field of mosquito-repellent textiles have published their findings from various institutions and nations. The bibliographic contexts were examined based on our search results for works on this subject, and the results are displayed here in various tables and graphs.

From the above figure (figure 1), it’s evident that the researcher got interested in this topic since 2014, and in our searching, no work was found before this. A total of 7 papers were reported in this year. Although the maximum amount of work has been done in the year 2022-2023, a total of 28 works has been published.

The most cited publications, together with their authors and year of publication, are shown in table 1. As can be seen, since its publication in the year 2010, ‘Microencapsulated citronella oil for mosquito repellent finishing of cotton textiles’ by Specos *et al* has garnered a maximum of 195 citations [57]. With 95 and 69 citations, respectively, ‘Effectiveness and cost-effectiveness against malaria of three types of dual-active-ingredient long-lasting insecticidal nets (LLINs) compared with pyrethroid-only LLINs in Tanzania: a four-arm, cluster-randomised trial’ [35] and ‘Bioengineering of a cellulosic fabric for insecticide delivery via grafted cyclodextrin’ [30] came in second and third. Among the recent works, ‘Micro- and nano-encapsulation of limonene and permethrin for mosquito repellent finishing of cotton textiles’ by Turkoglu *et al* received the maximum 43 citations [62] along with a work titled ‘Pyrethroid resistance alters the blood-feeding behavior in Puerto Rican *Aedes aegypti* mosquitoes exposed to treated fabric’ published by Agramonte *et al* back in 2017 [64].



Works from different countries were indexed in the database, among which India, the USA, and the UK attained the top position by publishing 34, 18, and 14 papers respectively, as shown in figure 2. After these countries, China, Tanzania, Egypt, Malaysia, Pakistan, Canada, and Kenya came to the top 10 contributing countries list.

Table 2 lists the journals that published the most papers in the research on ‘Mosquito repellent textiles.’ The Textile Institute Journal leads the list with nine papers, followed by Malaria Journal and International Dyer, with eight and five papers, respectively.

The authors of the majority of the works in this topic are depicted in figure 3. With 13 and 11 reported works, respectively, Sheikh, J. and Singh, A. top the list, followed by Rowland, M., Chavan, P.P., and Kaur, H.

3. Mosquito repellent agents

3.1. Synthetic mosquito repellent agents

Chemical substances called synthetic mosquito repellents help prevent mosquitoes from biting or landing on people. Commonly used synthetic mosquito repellents include DEET (N, N-diethyl-m-toluamide), permethrin, picaridin, etc.

3.1.1. DEET ($C_{12}H_{17}ON$)

The synthetic mosquito repellent DEET (figure 4(a)) is thought to be highly effective [65]. In order to repel insects such as mosquitoes, fleas, leeches, blackflies, and ticks, DEET is mainly applied topically. In insect repellent formulations, DEET is available in dosages ranging from 4% to nearly 100%. These formulations include lotions, creams, aerosols, gels, pump sprays, and impregnated towelettes. Typically, an ethyl or isopropyl base is used. For human skin, a minimum DEET evaporation rate of $5 \mu\text{gcm}^{-2} \text{h}^{-1}$ or $0.03 \mu\text{molcm}^{-2} \text{h}^{-1}$ was found over a period of 5–15 min. Then, DEET works as a volatile substance to keep mosquitoes away from their host for at least 38 cm [15]. Padding and microencapsulation are the most often used procedures for creating mosquito-repellent textiles made of cotton [2]. DEET was modified through a nitration and reduction process to create 4-Amino-N, N-diethyl-3-methylbenzamide (Modified DEET) and applied to cotton fabric using a crosslinking agent, dimethylol dihydroxy ethylene urea (DMDHEU) in a padding bath, followed by pad-dry-cure method [66]. Teli & Chavan also used this modified DEET and synthesized the reactive dye through a series of chemical reactions to create a dye with mosquito-repellent properties. The reactive dye was then applied to nylon 6 fabric using a dyeing cum finishing process [65]. Diazotization of the same modified DEET was done to make diazotized-based solution (Azotized DEET- NH_2), and the naphtholated cotton fabric was reacted with the solution. Henna and

Table 1. Papers with the highest citation.

Year	Title	Author	Citation	References
2010	Microencapsulated citronella oil for mosquito repellent finishing of cotton textiles	Specos M.M.M., Garcia J.J., Tornesello J., Marino P., Vecchia M.D., Tesoriero M.V.D., Hermida L.G.	195	[57]
2022	Effectiveness and cost-effectiveness against malaria of three types of dual-active-ingredient long-lasting insecticidal nets (LLINs) compared with pyrethroid-only LLINs in Tanzania: a four-arm, cluster-randomised trial	Mosha J.F., Kulkarni M.A., Lukole E., Matowo N.S., Pitt C., Messenger L.A., Mallya E., Jumanne M., Aziz T., Kaaya R., Shirima B.A., Isaya G., Taljaard M., Martin J., Hashim R., Thickstun C., Manjurano A., Kleinschmidt I., Mosha F.W., Rowland M., Prototop-off N.	95	[35]
2005	Bioengineering of a cellulosic fabric for insecticide delivery via grafted cyclodextrin	Romi R., Lo Nostro P., Bocci E., Ridi F., Baglioni P.	69	[30]
2007	N, N-diethyl-m-toluamide-containing microcapsules for bio-cloth finishing	Fei B., Xin J.H.	64	[58]
2008	DEET microencapsulation: a slow-release formulation enhancing the residual efficacy of bed nets against malaria vectors	N'Guessan R., Knols B.G.J., Pennetier C., Rowland M.	56	[59]
2013	Evaluation of commercial products for personal protection against mosquitoes	Revay E.E., Junnila A., Xue R.-D., Kline D.L., Bernier U.R., Kravchenko V.D., Qualls W.A., Ghattas N., Muller G.C.	53	[60]
2005	Evaluation of KO-Tab 1-2-3 [®] : A wash-resistant 'dip-it-yourself' insecticide formulation for long-lasting treatment of mosquito nets	Yates A., N'Guessan R., Kaur H., Akogbeto M., Rowland M.	52	[61]
2020	Micro- and nano-encapsulation of limonene and permethrin for mosquito repellent finishing of cotton textiles	Turkoglu G.C., Sariisik A.M., Erkan G., Yikilmaz M.S., Kontart O.	43	[62]
2009	Pyrethrum: A mixture of natural pyrethrins has potential for malaria vector control	Duchon S., Bonnet J., Marcombe S., Zaim M., Corbel V.	36	[63]
2017	Pyrethroid resistance alters the blood-feeding behavior in Puerto Rican <i>Aedes aegypti</i> mosquitoes exposed to treated fabric	Agramonte, N.M., J.R. Bloomquist, and U.R. Bernier.	35	[64]

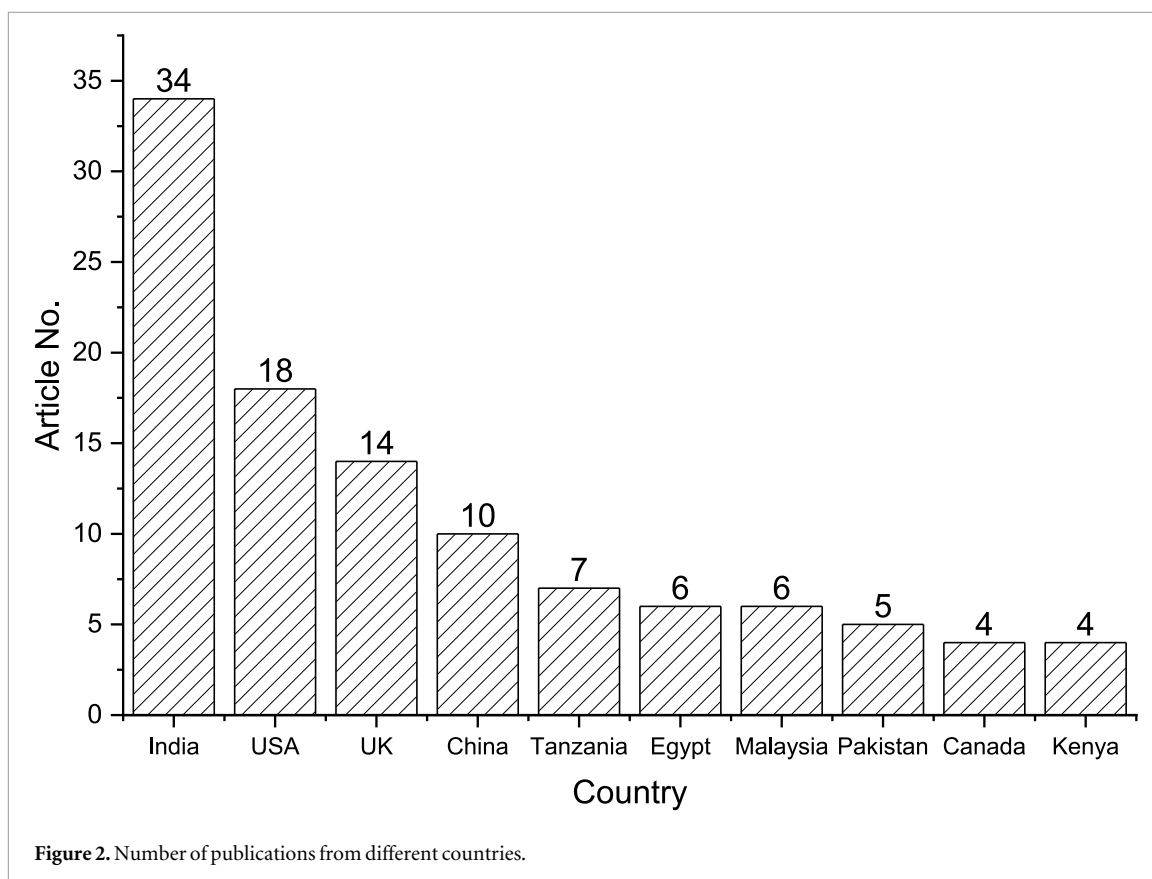
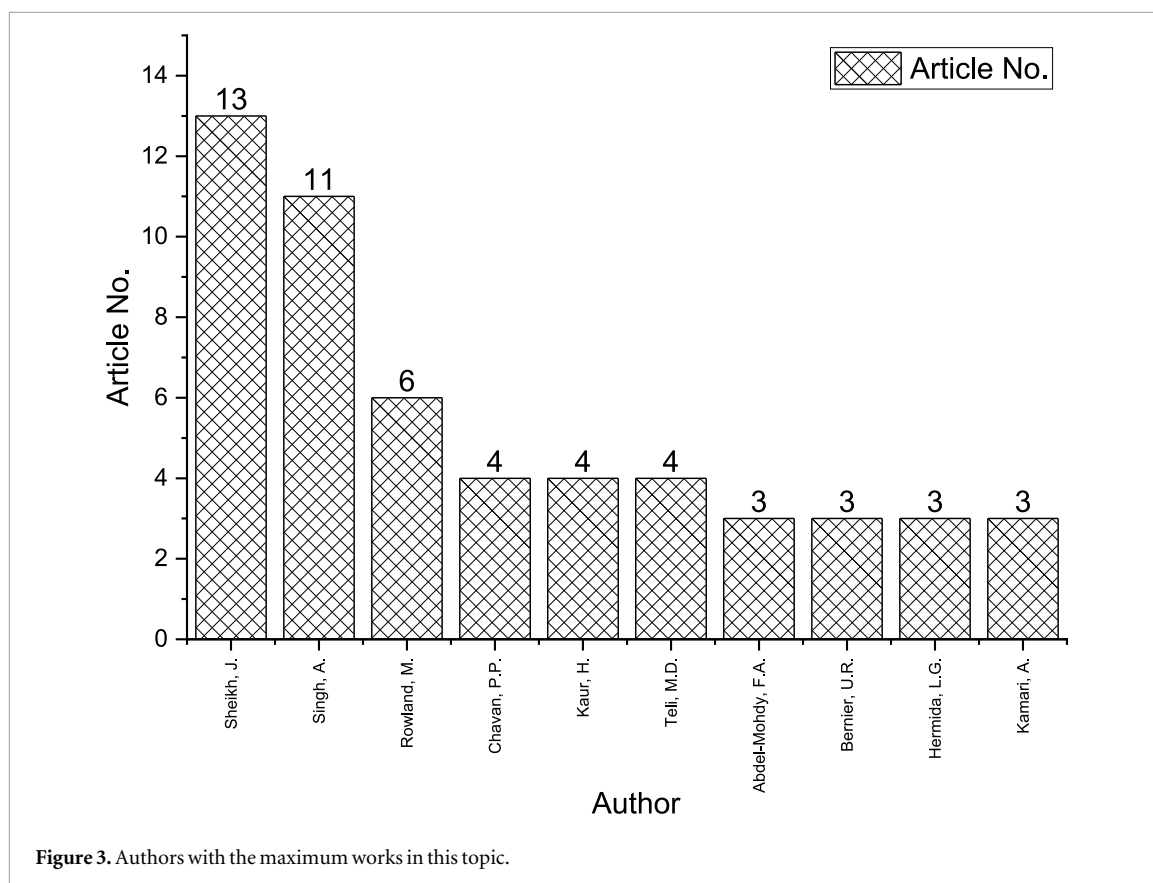


Table 2. List of the journals with the highest number of publications.

Name of the journal	Number of publications
Journal of the Textile Institute	9
Malaria Journal	8
International Dyer	5
Parasites and Vectors	4
Fibers and Polymers	4
Carbohydrate Polymers, Heliyon, Indian Journal of Fibre and Textile Research, Industrial Crops and Products, Insects, Journal of Natural Fibers, Journal of the American Mosquito Control Association, Man-Made Textiles in India, Parasitology Research, PLoS Neglected Tropical Diseases, Research Journal of Textile and Apparel, Textile Magazine, Transactions of the Royal Society of Tropical Medicine and Hygiene.	2

catechu were kept in an equimolar proportion to the expended quantity of base solution. Next, the azo dyes in the reaction mixture were synthesized, leading to the development of azoic colorants that repel mosquitoes [2]. Mosquito repellent disperse colorant was developed by the synthesis of 4–4-hydroxy coumarin with the azotized DEET-NH₂ [67]. Exhaust process of cross-linker-free finishing with DEET-NH₂ was also incorporated without the presence of cross-linker, binder, or dye molecules [68]. DEET was incorporated into the core of the bicomponent fibers for controlled release. The fibers were made into garments meant to keep mosquito bites off the ankles and feet. Even after twenty cold washes, the cloth remained 100% resistant. After the 25th wash, the fabric showed signs of partial repellent effectiveness [69]. DEET was incorporated in microencapsulation. In a DEET microencapsulation formulation, the repellent is progressively released from a capsule that holds it together. Over the course of the 6-month study period, the microencapsulated DEET formulation consistently



inhibited mosquito penetration, demonstrating a sustained repellent efficacy. On the other hand, the repellency of the conventional topical DEET formulation decreased with time [59]. DEET and picaridin-loaded recycled PET microfibers are developed and evaluated, marking the initial investigation of combined repellent loading (DEET/picaridin) through electrospinning [20]. Additionally, DEET was used as a carrier in the dyeing of aramid fiber with disperse dyes to improve dyeability [70]. Optimal protection can be achieved by developing a slow-release mechanism for DEET and ensuring its effectiveness in field testing. By extending the duration of depletion, the slow release can prevent excessive consumption of DEET. An experiment with bed nets showed the feasibility of this approach. However, the DEET nets felt greasy and sticky, while the odor was also considered unpleasant overnight. This indicates that more research is needed to develop a more pleasant repellent for slow-release products or adjust the DEET manufacturing process for commercial use. This could potentially allow people worldwide to benefit from the strong repellent properties of DEET bed nets [15].

Summary and outcomes of DEET impregnation in textile fabrics are given in tables 3 and 4, respectively.

Modification of DEET:

Step 1- Nitration pathway for preparing N, N-diethyl-3-methyl-4-nitrobenzamide from DEET.

A synthesis of N, N-diethyl-3-methyl-4-nitrobenzamide (DEET-NO₂) was conducted with potassium nitrate. First, the proper quantity of sulfuric acid 96% (47.5 mmol) was taken to 50 mmol of finely powdered potassium nitrate. The mixture was agitated at room temp. for 15 min. To form a homogenous slurry, 25 ml of dichloromethane was added, followed by vigorous stirring while cooling to 0 °C. After that, DEET (5 mmol) in DCM (8 ml) was poured dropwise while being stirred occasionally at room temperature. TLC was used to track the reaction's development. The resulting mixture was transferred into a container with ice cubes, followed by a neutralization process using pellets of sodium hydroxide (10%), and separation with the help of ethyl acetate. The water layer had been taken out using a separating funnel. Finally, the solvent was evaporated using a Rota evaporator, yielding an oil with a yellowish tint as the final product (figure 5(a)) [65, 66].

Step 2- Synthesis of 4-amino-N,N-diethyl-3-methylbenzamide via reduction of nitrated DEET. To a 5% sodium hydroxide solution (20 ml) in which DEET-NO₂ (2.05 g) had been dissolved, sodium sulfide flakes (3.9 g, 0.0055 mol) were added. Four hours of refluxing was followed by the cooling of the reaction mixture and filtration. With 40 milliliters of strong hydrochloric acid, the deposit of filtration was meticulously counter-balanced to pH 8. To get rid of contaminants, the mixture was filtered out (figure 5(b)). The product was then obtained by vacuum-evaporating the filtrate [66].

Another approach of Reduction of nitrated DEET:

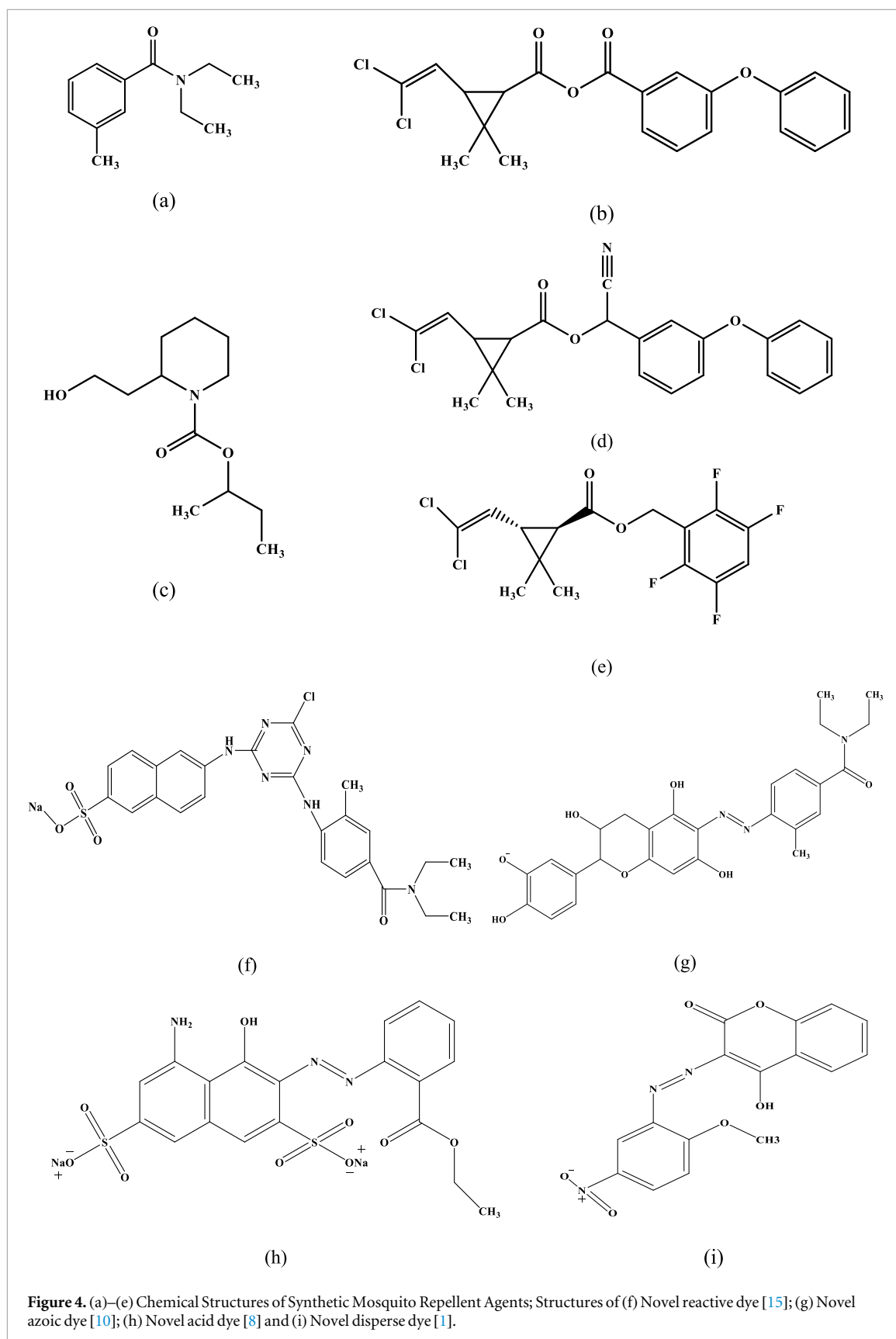


Figure 4. (a)–(e) Chemical Structures of Synthetic Mosquito Repellent Agents; Structures of (f) Novel reactive dye [15]; (g) Novel azoic dye [10]; (h) Novel acid dye [8] and (i) Novel disperse dye [1].

In a two-necked flask, a solution of DEET-NO₂ (12 mmol) in a mixture of water and ethanol (30:70, 28 ml) was prepared. The flask was charged with zinc powder (7 eq.), followed by the dropwise addition of concentrated hydrochloric acid (36%, 140 mmol) under room-temperature conditions. The reaction mixture was then heated at 70 °C–75 °C for four hours. The progress of the reaction had been monitored using TLC and

Table 3. Summary of DEET integrated mosquito-repellent textiles along with impregnation and evaluation method and major ingredients required.

Method of repellency	Major ingredients	Textile material	Impregnation method	Repellency evaluation	References.
Absorption Process	Poly (ethylene-co-vinyl acetate), EVA, as the core of the bio-component filament	High-density polyethylene (HDPE), as the sheath polymer	DEET absorption by EVA pellets which yielded swollen EVA pellets that contained 40 wt% DEET.	Foot-in-cage test	[69]
Crosslinked with DEET-NH ₂	Dimethylol dihydroxy ethylene urea, as a crosslinking agent, and other catalysts are SARASOFT-UT (silicone softener), magnesium chloride, and ethanol	Woven Cotton fabric	Pad-dry-cure	Arm-in-cage test	[66]
Dyeing cum finishing with DEET-NH ₂	Reactive dye, Sodium 6-((4-(diethylcarbamoyl)-2-methylphenyl)amino)-1, 3, 5-triazin-2-yl) amino naphthalene-2-sulfonate	Nylon 6 fabric	Reactive dyeing	Arm-in-cage test	[65]
Dyeing cum finishing with Azo-tized DEET-NH ₂	Henna and catechu as natural dyes (coupler), HCL and Sodium nitrite for diazotization, buffer solution of acetic acid and sodium acetate for neutralization	Woven Cotton fabric	Synthesis of the azo dyes by coupling of naphtholated cotton fabric in the reaction mixture	Arm-in-cage test	[2]
Dyeing cum finishing with Azo-tized DEET-NH ₂	Disperse dye, 4-hydroxy coumarin. HCL and Sodium nitrite for diazotization, buffer solution of acetic acid and sodium acetate for neutralization	Scoured Polyester fabric	Disperse dyeing	Arm-in-cage test	[67]
Mosquito-repellent-cum-anti-bacterial finishing	Acetic acid	Nylon 6 fabric	Exhaust process of cross-linker-free finishing with DEET-NH ₂	Arm-in-cage test	[68]
Microencapsulation	Melamine microcapsule	Polyester Net	Applying the DEET formulations to polyester netting.	Tunnel test	[59]
Where DEET is the core part					

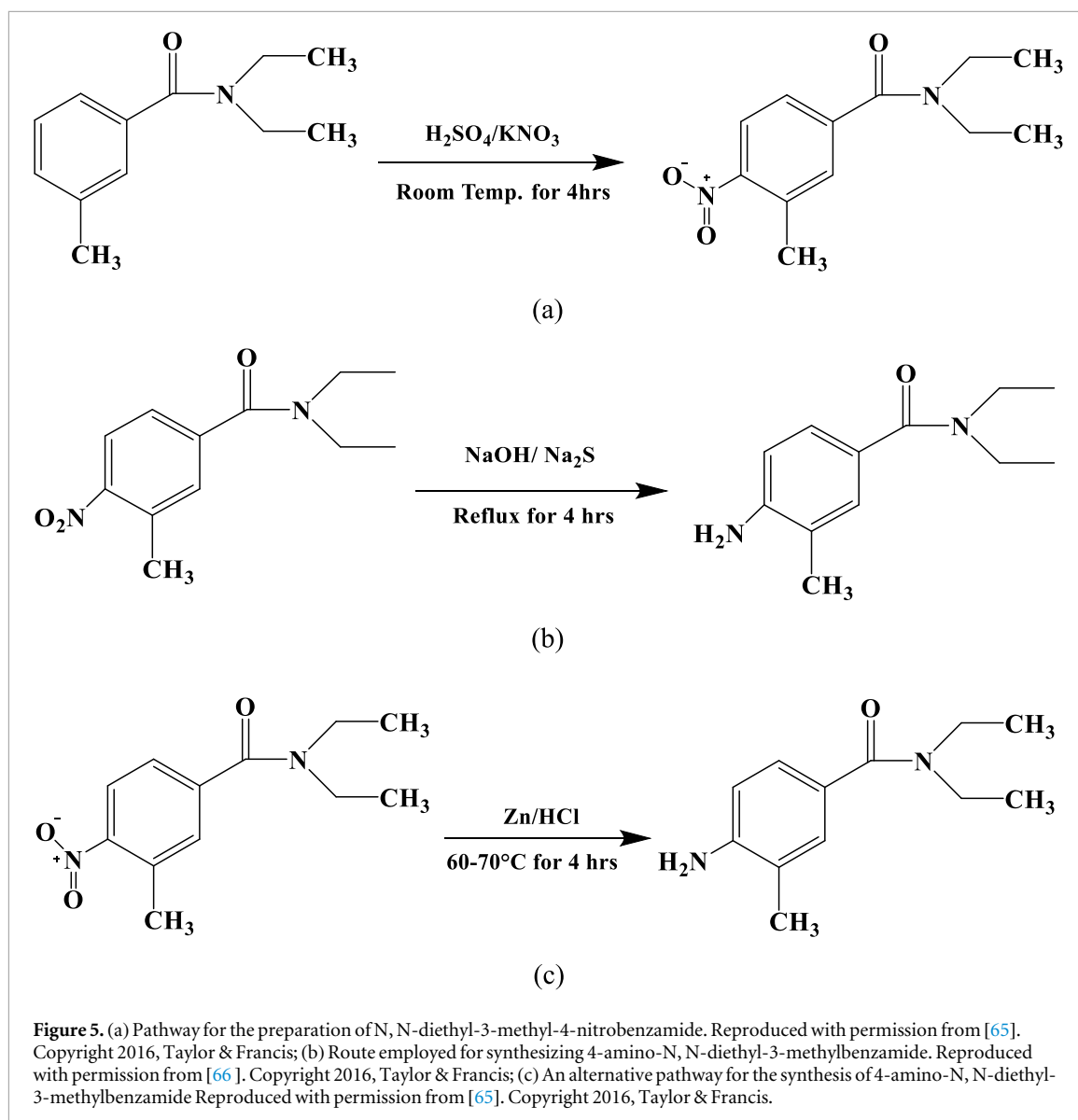
Table 4. Performance of DEET integrated mosquito-repellents textiles.

Textile material	Wash resistance test	Outcomes of both repellent and resistance test	Reference
High density polyethylene (HDPE), as the sheath polymer	Arm-in-cage test	The sock demonstrated remarkable residual efficiency with >90% protective efficacy after 20 weeks held at laboratory settings in the foot-in-cage repellent test. Even up to week 33, the sock showed some efficiency as a repellent. Even after 20 cold washes, the fabric remained 100% efficient at repelling insects. After the 25th wash, the fabric exhibited some efficiency as a repellent.	[69]
Woven Cotton fabric	ISO II	For roughly 10 washings, the fabric provided a good level of mosquito repellency and durability.	[66]
Nylon 6 fabric	ISO II,	Good mosquito repellency.	[65]
Woven Cotton fabric	ISO 105-C10	Good fastness properties like light, wash and rubbing.	[2]
	ISO 105-C06:1994	The resulting dyed materials had high to outstanding UV protection, over 87% antibacterial activity, and 100% mosquito-repellency. After 10 washing sessions, dyed samples with catechu extracted in a 5% depleted amount likewise maintained antibacterial activity (%) > 94.	[2]
Scoured Polyester fabric	ISO 105- C06	100% mosquito repellency was demonstrated by dyed polyester, which also exhibited other useful qualities as UV protection (UPF > 124) and antibacterial activity (> 93%). Even after 20 washings, a sizable portion of the mosquito-repelling ability persisted. The produced colors also shown reduced algal toxicity and effective antioxidant action.	[67]
Nylon 6 fabric	AATCC61-A	The finished fabric exhibits 100% mosquito repellency and >90% antibacterial activity, both of which are shown to be durable through at least 10 washings. Despite 10 washing sessions with 5% (owf) DEET-NH ₂ , the sample still exhibits 95.63% antibacterial activity against <i>S. aureus</i> and 92.45% antibacterial activity against <i>E. coli</i> . The amino group of DEET-NH ₂ can effectively provide antibacterial action to nylon that has been treated.	[68]
Polyester Net	Not specified	During the 6-month evaluation period, mosquito penetration was consistently inhibited by the microencapsulated DEET formulation, demonstrating a sustained repellent effect. On the other hand, the traditional topical DEET formulation shown a gradual decline in repellency. In addition, the 6-month duration of the microencapsulated DEET formulation's prolonged blood-feeding inhibition and mosquito mortality rates suggested that it would have enduring effectiveness against malaria vectors.	[59]

Ehrlich's reagent. An aqueous solution of 10% sodium hydroxide was used to bring the mix's pH down to 6-7 (figure 5(c)) [65].

3.1.2. Permethrin ($C_{21}H_{20}Cl_2O_3$)

Permethrin (figure 4(b)) is a synthetic insecticide that belongs to the pyrethroid family of chemicals. It is a potent, fast-acting insecticide originally obtained from the crushed dried flowers of the daisy *Chrysanthemum cinerariifolium* [71]. Permethrin acts as a contact insecticide, poisoning the nervous system of insects, leading to death or incapacitation. One of the projects emphasized developing distinctive cotton textiles with anti-mosquito features. Experimental designs were crafted to integrate potent insecticides such as permethrin and bioallethrin into the macromolecular structure of the adapted cotton fabrics. The process involved grafting glycidyl methacrylate, either independently or alongside β -cyclodextrin, and subsequently irradiating with a fast electron beam to chemically alter the cotton [72]. To reduce malaria morbidity and mortality, cotton fabrics were treated with permethrin and grafted with monochlorotriazinyl- β -cyclodextrin (MCT- β -CD) permanently for controlled-release [73]. Since permethrin is the only insecticide that is authorized for use on clothing, it is commonly used to treat fabric to make it repel mosquitoes. Once applied to the fabric, the pesticide loses its effectiveness after a specific number of washing cycles. This study mainly focuses on ToF-SIMS, which is used to quantify and identify mosquito repellents or insecticides [23]. Several nations, both



military and civilian, utilize synthetic pyrethroid permethrin applied to fabric to deter arthropod vectors. This study aimed to embed permethrin into army uniform fabric and assess its efficacy in repelling and eliminating unfed female *Aedes aegypti* mosquitoes under laboratory conditions [71]. This study investigated the effectiveness and longevity of protection offered by clothing treated with permethrin, with the aim of preparing for a potential randomized controlled trial. The trial would involve using school uniforms treated with permethrin to safeguard children against dengue fever [74]. Permethrin-treated 100% Cotton fabric and permethrin-treated Cotton-Polyester blend fabric (50% cotton/50% polyester) were used against *Ae. Albopictus* and *Aedes aegypti* followed by two exposure methods, e.g., petri dish and WHOPES cone method [75].

Summary and outcomes of permethrin impregnation in textile fabrics are given in tables 5 and 6 respectively.

3.1.3. Picaridin ($C_{12}H_{23}O_3N$)

The 1980s saw the development of picaridin, a DEET substitute created by Bayer that has been shown to be more efficient than DEET and does not have the same harmful qualities. One possible platform to achieve this is through the encapsulation of active substances, like insect repellents, in microcapsules (MCs). Using an antimicrobial polymer, PHMB, as the shell, MCs with antibacterial and antifungal properties were created, and the encapsulation of an insect repellent, picaridin (figure 4(c)), is described. MCs have a positive zeta potential, are uniform, and are spherical. According to GC data, picaridin loading levels display both antibacterial and antifungal activities, and they are more than 10 times the minimum dose for repelling mosquitoes. Four-week storage research shows that the concentration of picaridin does not significantly decrease [21].

Table 5. Summary of permethrin integrated mosquito-repellent textiles along with impregnation and evaluation method, and major ingredients required.

Method of Repellency	Major Ingredients	Textile Material	Impregnation Method	Repellency Evaluation	References
Grafting with GMA or GMA & β -CD or GMA & Permethrin. Retreatment	Permethrin and bioallethrin as the repellents, glycidyl methacrylate (GMA)	Duck Cotton fabrics	Immersion process	Bioassay test	[72]
Grafting of MCT- β -CD	Permethrin and bioallethrin as the repellents	MCT- β -CD-finished cotton fabrics as treated sample, a control sample of cotton fabric (untreated)	Padding	Bioassay test	[73]
Not specified	Permethrin as the repellent (added to the substrate, High density polyethylene)	Cotton/Nylon netting fabric	Topically treated with permethrin	ToF-SIMS imaging and quantification using ion implantation	[23]
Not specified	Permethrin as the repellent, acetone and a binder sodium laurel sulfate (1%)	Cotton-Polyester blend (65% cotton and 35% polyester)	Immersion method	Cone bioassay and cage bioassay	[71]
Not specified	0.52% w/w permethrin on factory-dipped clothing (FDC) and factory dipped school uniforms (FDSU) and 0.50% permethrin on Home dipped clothing (HDC) and Microencapsulated clothing (MC)	FDC: 100% cotton, HDC: 100% cotton, MC: synthetic blend, FDSU: Standard cotton	Polymer coating, micro-encapsulation, absorption	WHOPES cone tests and arm-in-cage assays	[74]
Not applicable	Not applicable	Permethrin treated 100% Cotton fabric and permethrin treated Cotton-Polyester blend fabric (50% cotton/50% polyester)	Not applicable	Petri dish exposure method and WHOPES cone method	[75]

Table 6. Performance of permethrin integrated mosquito-repellents textiles.

Textile material	Outcomes of both repellent and resistance test	References
Duck Cotton fabrics	The results indicate that increasing the fixed amount of cyclodextrins, which absorb the insecticide through their cavities, enhances the insecticide content in the final fabrics. Bioassay test results suggest that finished cotton fabrics exhibit rapid mosquito-repelling characteristics.	[72]
MCT- β -CD-finished cotton fabrics as treated sample, a control sample of cotton fabric (untreated)	According to bioassays, treated fabrics repel mosquitoes quickly. By increasing the concentration of insecticide in the treated fabrics as well as the exposure durations, the toxic activity of the treated materials increased. The findings demonstrate that, while treated fabrics retain a high level of insecticides, washing causes significant losses of the effective insecticides in control samples.	[73]
Cotton/Nylon netting fabric	Quantification using ion implantation, which has been applied to mosquito netting, is not effective on topically treated fabrics made of cotton and nylon fibers due to the varying secondary ion yield of the insecticide characteristic ion between the two fiber types. In a cross-sectional analysis using ToF-sims, it was observed that the insecticide is eliminated from cotton more easily than from nylon after 10 washes. However, the ratios of the remaining insecticide amount in cotton and nylon were alike after 30 washes. Permethrin was discovered to fully penetrate the fibers during its application.	[23]
Cotton-Polyester blend (65% cotton and 35% polyester)	The initial wash removed 93.33% of mosquitoes after one hour, with effectiveness declining gradually up to the fifty-fifth wash. More washes led to increased mosquito landings on the permethrin-treated cloth compared to untreated fabric. All mosquitoes exposed to permethrin-treated material perished within 24 h.	[71]
FDC: 100% cotton, HDC: 100% cotton, MC: synthetic blend, FDSU: Standard cotton	During cone testing, variations in effectiveness between factory-dipped and microencapsulated textiles were observed. Factory-dipped clothing exhibited the most significant impact on knockdown (KD) rates (3 min: 38.1%, 1 h: 96.5%) and mortality (97.1%). No significant distinction was found between factory-dipped clothing and factory-dipped school uniforms. Consequently, garments treated with the factory-dipped method were selected for further examination. In arm-in-cage trials, factory-dipped attire showed a complete cessation of biting and a 59% reduction in landings (95% CI = 49.2%–66.9%). The duration and manner of washing significantly affected the results; machine washing had a longer insecticidal lifespan (LW50 = 33.4) compared to simulated hand washing (LW50 = 17.6). Ironing post one week of simulated use led to a substantial reduction in permethrin levels, with a 96.7% decrease after three months.	[74]
Permethrin treated 100% Cotton fabric and permethrin treated Cotton-Polyester blend fabric (50% cotton/50% polyester)	The research revealed that, <i>Ae. albopictus</i> knockdown (mean \pm standard error) was highest at $37 \pm 0.04\%$ and mortality at $46 \pm 0.09\%$ on unwashed treated fabric. Conversely, the lowest rates were observed for this mosquito species at $9 \pm 0.02\%$ for knockdown and $14 \pm 0.03\%$ for mortality in the 15-wash group of fabrics. Permethrin levels in unwashed 100% cotton fabric were $29.2 \pm 2.9 \mu\text{g cm}^2$, whereas levels in unwashed 50% polyester/50% cotton fabric were $6.3 \pm 1.0 \mu\text{g cm}^2$. However, Insect Shield stated that $125 \mu\text{g cm}^2$ of permethrin were applied to the fabric.	[75]

3.1.4. Cypermethrin ($C_{22}H_{19}Cl_2NO_3$)

Cypermethrin (figure 4(d)), a pyrethroid insecticide, is recommended by the World Health Organization as moderately toxic. In a study, the effectiveness and lasting effect of cotton fabrics treated with a finishing formulation containing cypermethrin, polyvinyl acetate (PVAc) polymer, and dimethylol dihydroxy ethylene

urea (DMDHEU) crosslinker was demonstrated. Both surface-coating and immersion impregnation techniques were evaluated, revealing that the coating method is significantly more efficient than impregnation. The treated samples show a high level of insect repellency. Based on the bioassay results, treated fabrics maintain their efficacy for up to 18 months at room temperature (25 °C). Additionally, washing fabrics treated with pesticides does not notably reduce the insecticidal effect after multiple washes, as per the bioassay results. Cypermethrin emerges as a promising pesticide choice for mosquito nets due to these attributes [76].

3.1.5. Transfluthrin ($C_{15}H_{12}Cl_2F_4O_2$)

Transfluthrin (figure 4(e)) is a pyrethroid that, at sub-lethal levels, shows spatial repellent properties against mosquitoes [34]. Spatial repellents are compounds that can change mosquito feeding behavior without touching the chemical source. They are semi-volatile chemicals, emitted from treated fabric or burning repellent-containing materials, that induce an excito-repellency effect on mosquitoes without direct contact. These spatial repellents act on odor receptors in mosquito antennae, prompting behavioral alterations rather than toxic effects. Thus, mosquitoes need not land on treated surfaces to be affected. Continuous chemical release establishes a protective buffer zone, hindering blood feeding and parasite transmission, offering protection against vectors [77]. In the study, Functional Micro-Dispensers (FMDs) utilizing Micro-Electro-Mechanical-Systems (MEMS) were employed to disseminate spatial repellents such as transfluthrin, to diminish mosquitoes' capacity to feed on human blood. These trials involved integrating FMDs into a sleeve made of Flame Resistance Army Combat Uniform (FRACU) fabric [78]. A study was carried out to assess the impact of airborne transfluthrin from impregnated textile materials on two major malaria vectors, *Anopheles dirus* and *Anopheles minimus* [77]. Another study examined the efficacy of fabric strips treated with an emulsified concentrate of transfluthrin or microencapsulated Citriodiol[®] placed in open eave gaps on houses as a control measure to decrease *Anopheles arabiensis* bites outdoors. In certain mosquito populations, extensive cross-resistance to various compounds within the pyrethroid group has emerged due to repeated treatments over numerous years, as they share a similar mode of action. A study compared the topical toxicity of five insecticides to variations in blood-feeding activity in pyrethroid-resistant and pyrethroid-susceptible strains of *Ae. aegypti* exposed to pyrethroid-treated FRACU fabric sleeves. Notably, transfluthrin demonstrated reduced effectiveness in this context [64].

Summary and outcomes of transfluthrin impregnation in textile fabrics are provided in table 7.

3.1.6. Ethylenediamine ($C_2H_8N_2$)

In order to shield people from dangerous insects, germs, free radicals, and UV radiation, multifunctional textiles that repel mosquitoes are an intriguing invention. This study employed a novel technique of *in situ* azoic dyeing using ethylenediamine (EA), a synthetic yet harmless mosquito repellent, and Terminalia chebula natural dye as the coupling component. An arm in a cage was implied to evaluate repellency. 100% mosquito repellency that remained effective for at least 20 washes. Further functional characteristics were also verified, including UV protection (UPF >50), antioxidant activity (>87%), and antibacterial activity (>94%) [79].

3.2. Natural mosquito repellent agents

The functionalization of natural textile fibres using sustainable resources is becoming more and more popular as concerns about environmental and human safety increase. Because when chemicals like DEET is applied for extended periods of time and at high concentrations, it can have a variety of serious side effects, such as allergies, rashes, and skin redness, when used as a functional finishing material to repel mosquitoes [80].

3.2.1. Essential oil

The search for new repellents has become necessary due to mosquitoes' resistance to current chemicals over time. As an alternative to synthetic and chemical-based repellents, natural components such as essential oils (EO) derived from various plant sources can be utilized to repel mosquitoes. The utilization of essential oil micro- and nano capsules has also been investigated to enhance durability [81]. However, it is generally known that finishing products made from essential oils—like eucalyptus, rosemary, clove, lemon grass, peppermint, and castor oil—have strong repellent qualities and have little to no effect on the environment and unintended species. Due to their natural protective properties, essential oils are excellent repellents and insecticides. Eucalyptus oil, specifically, has a rich history as an antifungal, antibacterial, and antiseptic substance. Eucalyptus oil was employed as a core part in the microencapsulation process, whereas Moringa oleifera and Arabic gums were imparted as the outer shell of the microcapsules [80]. Citronella oil, a bio-based insect repellent, was coacervated using an ethyl cellulose shell for encapsulation [38]. In a different study, citronella oil served as the capsule's core and zinc oxide nanoparticles as its outer shell [82]. The core of cinnamon bark oil encapsulated in a chitosan-gelatin shell provides a controlled-release mechanism, providing outstanding

Table 7. Summary & performance of transfluthrin integrated mosquito-repellents textiles along with evaluation method and major ingredients required.

Method of repellency	Major Ingredients	Textile Material	Outcome	References
Functional Micro-Dispensers (FMDs) were fabricated using Micro-Electro-Mechanical-Systems (MEMS)	Transfluthrin (Spatial repellent)	Flame Resistance Army Combat Uniform (FRACU)	FMDs with transfluthrin provided superior protection from mosquito bites than permethrin-treated cloth, with a nearly 90% reduction in feeding.	[78]
Dipping method	Transfluthrin as the repellent	Burlap (hessian) fabric	Knockdown and mortality rates varied significantly along the gradient, with higher rates closer to the source. <i>An. minimus</i> was more susceptible to transfluthrin.	[77]
Microencapsulation of Citriodiol® with cotton fabric and hessian fabric was dipped in transfluthrin emulsified concentrate	Citriodiol® contains at least 64% PMD from <i>Eucalyptus citriodora</i> oil with a poly lactic acid shell with transfluthrin.	Cotton fabric and hessian fabric	Citriodiol® eave strips with microencapsulation failed to offer effective outdoor protection against <i>An. arabiensis</i> . Transfluthrin-sprayed strips decreased mosquito landing on human volunteers.	[34]
Solvent evaporation technique	Permethrin, etofenprox, deltamethrin, DDT & transfluthrin. Anhydrous Ethanol or acetone as the solvent for all repellents.	FRACU fabric	To combat pyrethroid-resistant mosquitoes, higher pyrethroid concentrations are required. Permethrin exhibits greater insecticidal efficacy than etofenprox, with a lower mammalian oral LD50 of >10,000 mg kg ⁻¹ compared to permethrin's 500 mg kg ⁻¹ . Deltamethrin required the least chemical for LD50 topical therapy against resistant strains, despite its high resistance ratio. DDT shows low resistance ratios.	[64]

Table 8. Summary of essential Oil (EO) integrated mosquito-repellent textiles along with impregnation and evaluation method, and major ingredients required.

Natural ingredients	Method of repellency	Major ingredients	Textile material	Impregnation method	Repellency evaluation	References
Eucalyptus oil as the core part, Moringa oleifera gum and Arabic gums as the outer shell of the different microcapsules	Micro-encapsulation by a complex coacervation method	Glutaraldehyde (acrylic binder) as the cross-linking agent, gelatin and acetic acid for the preparation of the microcapsules, Tween 20 (stabilizing agent)	Military camouflage-printed polyester/cotton blended fabric	Pad-dry-cure	Arm-in-cage test	[80]
Citronella oil as the core part	Micro-encapsulation by coacervation method	Ethyl cellulose as the outer shell, Tween 20 as a surfactant, alginate thickener as printing paste, acrylic coating polymer for coating processes, acrylic binding agent for impregnating	The fabric is a plain weave cotton blend (panama fabric with a weft/warp density of 12/60 threads per cm)	Direct printing, coating and impregnating of microcapsules	Cone test	[38]
Citronella Oil as the center part	Micro-encapsulation	ZnO nanoparticles as the outer part, dispersing agent, cationic surfactant	Net fabric (50 cm × 16 cm).	Coating by pad-dry-cure	WHO's glove method	[82]
Cinnamon Oil (core) and Chitosan-gelatin (shell)	Micro-encapsulation via optimized spray-drying technology	A low-temperature curable binder, acetic acid, ethanol, and n-hexane	Linen fabric	Pad-dry	Arm-in-cage test	[83]
Lemongrass oil as the core part	Micro-encapsulation	Gum acacia (Gelatin and gum Arabic) was used as wall material.	Knitted cotton fabric	Pad-dry-cure	The excito repellency chamber test	[84]
Lemongrass oil as the repellent	Oil in water nano-emulsion	Sodium sulfate and formaldehyde were used to obtain microcapsules. 1-octen3-ol used of electroantennography, Sorbitan monooleate (S-80) and sorbitan monolaurate (T-20), cationic and anionic polyelectrolytes (RF 8220 and RF 8162) for carrying out LBL	Nylon net fabric (60 GSM)	Layer-by-layer (LBL) deposition method	The excito repellency chamber test	[81]
Litsea, lemon as repellent.	Litsea-lemon EO micro-emulsion	Calcium chloride solution	Polyester and cotton fabric	functional antimicrobial cum mosquito-repellent coating by soak-pad-dry		[85]
Sodium. alginate solution and chitosan solution Lemon oil to impart fragrance, Pectin and gelatin are as repellent	Metal nanoparticles and oil encapsulation in biopolymer material	Nanoparticles (NPs) are AgNPs, ZnONPs, TiO ₂ NPs. Crosslinkers are sodium hypophosphite and citric acid	Cotton fabric (285 m ⁻²) and wool fabric (365 g m ⁻²)	Pad-dry-cure method	Arm-in-cage test	[26]

Table 9. Performance of essential oil (EO) integrated mosquito-repellents textiles.

Textile material	Outcomes of both repellent and resistance test	References
Military camouflage-printed polyester/ cotton blended fabric	In comparison to Arabic gum, moringa gum shows a higher repellency rate. The treated fabric containing 6% moringa gum exhibited 73.33% repellency even after 40 washings, whereas the treated fabric containing 12% Arabic gum showed 60% repellency. Despite being used less often due to its tougher texture (12.5% compared to 6%), moringa gum outperformed Arabic gum in the washing durability test.	[80]
plain weave cotton fabric	After washing, the insect repellent performance of the printing and coating method improved. Mosquito death rates for printing, coating, and impregnation were 72%, 65%, and 55%, respectively. Mosquitoes showed a tendency to avoid treated materials. Even after five wash cycles, the fabrics maintained their water repellency.	[38]
Net fabric (50 cm × 16 cm). After coating, the coated net was sewed into gloves	The laboratory samples were analyzed using a common bio-efficacy technique, revealing a 97.93% mosquito repellency. Furthermore, production-scale multifunctional mosquito repellent fabrics with a 92.15% mosquito repellency were manufactured from the pilot coating in industrial settings. Field evaluation also indicated that mosquito landings on volunteers inside bed nets constructed of this coated fabric were 30% lower than on those that were not coated.	[82]
Linen fabric	The finished linen boasts remarkable 100% mosquito repellency, exceptional antibacterial properties against <i>S. aureus</i> and <i>E. coli</i> , and durability lasting up to 20 washes. Additionally, the fabric retains a pleasant scent and strong, effective antioxidant properties.	[83]
Knitted cotton fabric	Fabrics containing cotton infused with lemongrass exhibit an impressive 90% efficacy in repelling mosquitoes. Post 30 wash cycles, the fabric maintains its enhanced wash resistance owing to the microencapsulation technique; following this period, the mosquito repellency rate only drops by 28.5%.	[84]
Nylon net fabric	Even after 25 washes, the materials maintained their scent, remained effective in repelling mosquitoes, and had antimicrobial properties, despite a decrease in mortality rate.	[81]
Polyester and cotton fabric	The assessment of <i>Aedes aegypti</i> mosquito repellency revealed 71 ~ 43% repellency, in contrast to 52 ~ 94% for neat EO-impregnated cotton. Fabrics treated with litsea and lemon EO microemulsion showed potent antibacterial activity against skin-associated microbes <i>S. aureus</i> , <i>S. epidermidis</i> , <i>T. rubrum</i> , and <i>E. coli</i> . The textiles also potentially possessed mosquito-repelling properties.	[85]
Cotton fabric	Higher mosquito repellent activity is obtained by treating fabrics with 5% TiO ₂ NPs encapsulated in pectin biopolymer; higher antimicrobial activity is obtained by treating fabrics with 5% AgNPs encapsulated in gelatin biopolymer; and increased Ultraviolet Protection Factor values are obtained by treating fabrics with 5% ZnONPs encapsulated in gelatin biopolymer. When compared to untreated fabric, the treated textiles' mechanical and physical properties function better.	[26]

mosquito repellency [83]. Lemongrass oil was also used for mosquito-repellency as the core part of the microencapsulation [84]. Furthermore, to achieve antibacterial and mosquito-repelling properties, an eco-friendly microemulsion technology was utilized to create a textile coating loaded with essential oil (EO) [85]. The layer-by-layer (LBL) technology was utilized to create a lemongrass oil nano emulsion that effectively combats microbiological growth and mosquitoes when applied to nylon net fabric [81]. By directly putting a separate metal nanoparticle containing natural polymers like pectin and gelatin to the fabric in the presence of lemon oil aimed to develop scented fabrics and textiles that repel mosquitoes [26]. Summary and outcomes of Essential Oil impregnation in textile fabrics are given in tables 8 and 9 respectively.

3.2.2. Plant extracts

With the emerging environmental concern extracts from natural sources, i.e., plant extracts as dye [86, 87], etc, and their extraction techniques [88] are gaining much importance. Many of these extracts have mosquito repellent properties within e.g., eucalyptus leaf extracts were employed to cotton fabric as both dye component and mosquito-repellent by natural dyeing-cum-multifunctional finishing [36]. Another study employed

Table 10. Performance of plant extracts integrated mosquito-repellents textiles along with impregnation and evaluation method and major ingredients required.

Natural ingredients	Method of repellency	Major ingredients	Textile material	Impregnation method	Repellency evaluation	References
Eucalyptus leaves as dye component and repellent,	Dyeing-cum-multifunctional finishing	Citric acid as cross-linking agent	Cotton fabric	Natural dyeing before padding on a two-bowl padding mangle	Arm-in-cage test	[36]
Eucalyptus leaf nanoparticles in the form of prints (pre and post calcinated forms)	Nano-technology	Myrobalan powder solution for dye (natural) fixation, seed powder of Cassia tora as gum, Copper sulphate as mordanting (simultaneous) agent	Plain weave cotton fabric (122 GSM and 200 thread count)	Screen Printing	Modified WHOPEs Excito chamber test method	[33]
Anacyclus pyrethrum (Akar-kara) plant	Finishing	Methanol	Cotton fabric	Direct application	Arm-in-cage test	[4]
Peppermint leaves, stems and garlic cloves mixture as repellent finish	Dyeing-cum-finishing	99.8% methanol, sodium-lauryl-ether-sulfate, and sodium benzoate for alcoholic extraction	Cotton knit fabric	Exhaust dyeing process	Cone bioassays test and a self-modified cage technique	[18]
Andrographis paniculata plant as the repellent	Direct application and micro-encapsulation method	Methanol for extraction, Sodium alginate and calcium chloride for preparing for microcapsules, citric acid as a binder	Dyed Cotton Rib fabric, Bio polished using cellulase enzymes from <i>Trichoderma reesei</i>	Pad-dry-cure method for direct application and exhaustion method for microencapsulation method	Mosquito Repellency Behavioral test	[42]
Pyrethrum (a mixture of natural pyrethrins)	Pyrethrum-based formulation	Acetone insecticide and silicone oil solutions were utilized as carriers for treating filter papers.	Long-lasting insecticidal nets (LLINs)	Pynet EC 5% formulation spraying	Cone bioassays test	[63]

eucalyptus leaf extracts to create printed textiles crafted with nanotechnology that are environmentally friendly and repel mosquitoes. Here, green synthesis method was used for the synthesis of nanoparticles using fresh eucalyptus leaves [33]. An herbal mosquito repellent finish was applied to cotton fabric samples, and the repellent's effectiveness was assessed. The active ingredient was extracted from different parts of the *Anacyclus pyrethrum* (Akarkara) plant [4]. Recently, various concentrations (5%, 15%, 25%, and 35%) of PGE (Peppermint Garlic Extract) solution were prepared and administered to the fabric produced using an exhaust dyeing method to assess the repellency of mosquitoes (*Aedes Aegypti L.*) [18]. A study explores using *Andrographis paniculata* herbal extract to develop an eco-friendly fabric that repels mosquitoes. The extract is applied to the fabric through microencapsulation or direct application, and a behavioral test is conducted to evaluate its effectiveness in repelling mosquitoes [42]. Pyrethrum is a mixture of natural pyrethrins (six organic esters derived from the flowers of a plant in the genus *Chrysanthemum*), synthetic versions known as pyrethroids used against pyrethroid-resistant *An. gambiae* in field situations. A comparison was established with standard pyrethroids (i.e., deltamethrin and permethrin) [63]. R. Priya *et al* used flowers of *Senna auriculata* bio extract for mosquito repellent finishing on woven cotton textiles, which showed a tendency of increased repellency according to the extract concentration [89]. However, Gopalkrishnan D. *et al* and Vijayalakshmi D. *et al* applied chrysanthemum flower extract and daisy flower extract, respectively, to make fabrics mosquito-repellent [90, 91]. Summary and outcomes of impregnation of plant extracts in textile fabrics are given in tables 10 and 11, respectively.

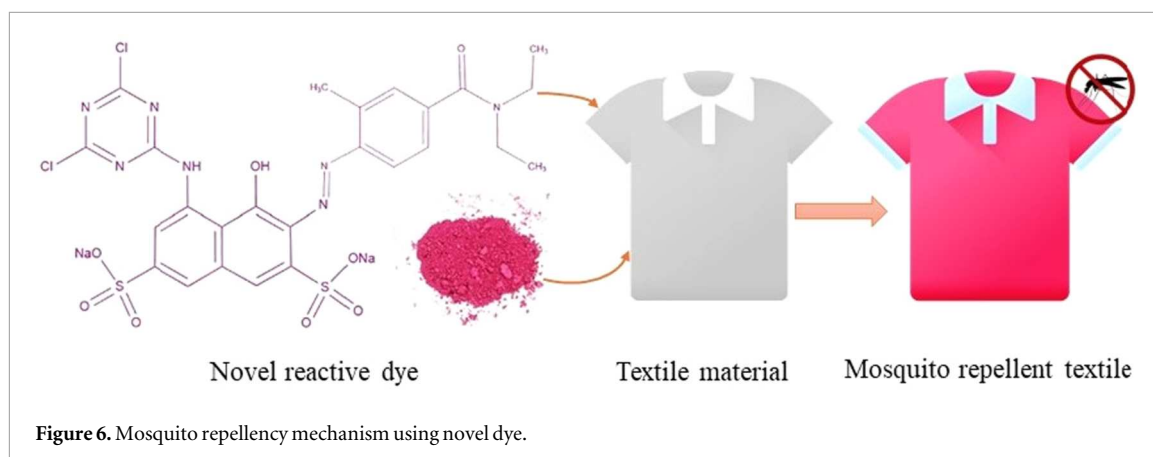
4. Repellency method

4.1. Dye synthesis

Mosquito-repellent dyes tend to repel mosquitoes, and fabrics treated with these dyes produce a colorful textile, providing functional property and adding to their aesthetic appeal, that is not only wash-durable but also repellent [1, 2]. Many studies have been conducted to attain this feature by incorporating a mosquito repellent agent i.e., N, N-diethyl-meta-toluamide (DEET), Ethyl anthranilate (EA) [2, 16, 79] etc into the structure of dye molecules (figure 6) so when the material is coloured with this novel dye it shows mosquito repellency. In two different studies by Teli *et al* and Singh *et al* cold-brand reactive dyes were made utilizing DEET to create novel dyes that were used in a dye-cum-finishing technique to impart color and functional property to Nylon 6 fabrics [65, 92]. Similar attempts to produce novel dyes were carried out by other researchers, where they formed modified disperse dye using DEET, EA [1, 67], and coumarin [1], where the dye showed satisfactory mosquito repellency when polyester fabrics were dyed using them. Out of all the reported work syntheses of Novel Azo dyes have attracted most researchers' attention [2] where the researcher tried to blend natural components i.e., Henna, Catechus [2], Terminalia chebula [79], chitosan [93] with DEET [2, 37, 93] or EA [79] to produce novel azo dyes or synthesize pure synthetic azo dyes [37] to impart color and functional properties to cotton fabric. On top of that, some additional works have also been reported, which studied the scopes of modifying acid dyes [2] and basic dyes [16] for the coloration of nylon and acrylic fabric, respectively. In another study conducted by Kantheti *et al* used Eucalyptus globulus leaf dye extract was used in nanoparticles form to print cotton fabric [33], whereas Endris *et al* used a similar extract to dye cotton fabric [36]. Further discussion and outcomes have been shown in tables 12 and 13 respectively. Figure 4 illustrates the structures of different types of novel dyes [1, 2, 65, 92].

4.2. Encapsulation

Micro and Nano encapsulation is a specialized process involving the encapsulation of small quantities of active chemicals, named core material, within a thin layer of polymers called shell/ wall, and produces micro- and nano-sized capsules respectively [62]. The difference in the microcapsule and nano capsule lies in the size of the core materials employed, normally a size of 1–100 nm spherical particles [3] is used in the formation of nano capsule, whereas the micro capsule found in different studies were in the range of 1–100 μm [94]. This technique enables the controlled release of these chemicals over an extended period. By encapsulating volatile substances, such as aroma compounds and Essential Oils (EO), encapsulation enhances their stability and protects them from various external factors like sunlight, evaporation, humidity, alkalinity, or mechanical agitation. The release mechanism of the encapsulated material depends on factors such as the composition, density, permeability, and biological properties of the shell material. This method plays a crucial role in effectively managing the release rate of volatile substances, thereby prolonging their lifespan and ensuring their controlled utilization [17, 95]. Numerous researchers have utilized this method to imbue textile fabrics and fibres with mosquito repellent properties. Some have employed the direct encapsulation technique to incorporate mosquito repellent agents, including both natural, such as essential oils [17, 28], and synthetic options like DEET, picaridin etc [21, 59] into capsules. Conversely, other researchers have applied

**Table 11.** Outcomes of plant extracts integrated mosquito-repellents textiles.

Textile material	Wash resistance test	Outcomes of both repellent and resistance test	References
Cotton fabric	ISO: 105-A02-1995	The final product has an insect repellency percentage of 92.79%. In addition, the aroma strength is 74.68%. Samples with ideal dyeing conditions had 100% bacterial reduction percentage for both gram-positive and gram-negative bacteria at the end of the insect repellent finish. The cross-linking agent citric acid improved the finishing's durability.	[36]
Plain weave cotton fabric (122 GSM and 200 thread count)	Modified WHOPEs Excito chamber test	According to the study, 10% pre- and post-calcinated nanoparticles can achieve 90% effectiveness. It may be inferred from this result that samples printed with 10% pre and post calcinate nanoparticles are highly effective in repelling mosquitoes, even after 10 washing cycles, and are commercially viable. To reduce mosquito access, these materials can be used for doorway screens and curtains.	[33]
Cotton fabric	ISO 105- C06	Cotton fabric samples treated with Akarkara flower extract exhibited the highest level of mosquito repellency. According to experimental research, the ability of completed cotton fabric samples to repel mosquitoes ranged from 57.87 to 79.63%. Furthermore, it was discovered that the extract's mosquito-repelling effectiveness increased in proportion to its concentration. Following a single wash, the mosquito repellency of the cotton fabric sample decreased from 79.5 to 24.2%, and this trend persisted with every subsequent wash.	[4]
Cotton knit fabric	ISO 105- C06: 2010	According to the findings, fabric samples treated with 25% PGE and 35% PGE exhibited the highest mosquito mortality rates (50.00% and 76.67%, respectively) and repellency levels (78.6% and 85.6%, respectively).	[18]
Dyed Cotton Rib fabric	Not specified	Upon completion, the fabrics exhibited 96% repellent activity through direct application and 94% activity by microencapsulation. While the direct application method demonstrated mosquito repellent action for only 10 washes, the microencapsulation method shown good activity for up to 30 washes.	[42]
Long-lasting insecticidal nets (LLINs)	Not specified	In the lab, mosquito nets treated with 500–1,000 mg m ⁻² (pyrethrum) remained effective for nine months, causing >80% mortality and/or >95% K _D impact. Yet, there were conflicting findings on the efficacy and longevity of pyrethrum (Pynet 5% EC) on substrates, especially on mud, a porous medium showing <80% mortality at 2 g m ⁻² after 3 months.	[63]

Table 12. Synthesis process and impregnation method of mosquito-repellent dyes.

Dyes	Major ingredients	Synthesis process	References
Novel Reactive Dye	N, N-Diethyl-3-methylbenzamide (DEET), Potassium Nitrate, 2, 4, 6-Trichloro-s-triazine (TCT)	At first N, N-diethyl-3-methyl-4-nitro benzamide (DEET-NO ₂) was synthesized from potassium nitrate to be used in the synthesis of 4-Amino-N, N-diethyl-3-methyl benzamide (DEET-NH ₂) which later on used to produce Sodium 6-((4-(diethyl carbamoyl)-2methylphenyl) amino)-1, 3, 5-triazin-2-yl) amino) naphthalene-2-sulfonate	[65]
	H-acid (Sodium 4-Amino-5-hydroxy-2,7-naphthalene Di sulfonate hydrate), cyanuric chloride, N, N-diethyl-3methylbenzamide (DEET)	Cyanuric H-acid was prepared from Cyanuric chloride and H-acid and DEET was modified using Sodium nitrite (NaNO ₂) to form DEET-NH ₂ (modified DEET) which diazotized on later. The diazotized modified DEET was added to cyanuric H-acid solution for coupling reaction which finally produced the reactive dye.	[92]
Novel Disperse Dye	DEET, EA, 4-hydroxy coumarin	At first modified DEET (DEET-NH ₂) was produced using nitric acid and sulfuric acid. The DEET-NH ₂ and EA (Base) were coupled with 4-hydroxy coumarin to produce two disperse dye namely dye1, dye 2.	[67]
	2-methoxy-5-nitroaniline, 4-hydroxy coumarin	2methoxy-5-nitroaniline was diazotized using hydrochloric acid and sodium nitrite (NaNO ₂). Later this diazonium salt was coupled with the coupler (4-hydroxy coumarin) in a coupling reaction to form an azo disperse dye.	[1]
Novel Azo Dye	DEET; Henna and catechu as natural dyes	DEET was modified to DEET-NH ₂ using hydrochloric acid (HCl) and NaNO ₂ . Henna and catechu were crushed and the dye was extracted using Soxhlet apparatus. Solution of this extracts were used in naphtholation of cotton fabrics. The naphtholated cotton fabric and diazonium salt were reacted in a coupling reaction at 40 °C for 1h which developed the dye.	[2]
	ethyl anthranilate (EA), Terminalia chebula natural dye	EA was diazotized using HCl and NaNO ₂ and coupling agent from Terminalia chebula extract was prepared. Cotton fabric naphtholated using the coupling agent were reacted with the diazotized EA to develop azo dye on the fabric.	[79]
	N, N-diethyl-m-toluamide (DEET), Napthol ASG, Naptol ASBS and Napthol ASBO	Naphthols were made into solution which later on reacted with modified DEET (DEET-NH ₂); modified using HCl and NaNO ₂ , to get the azoic dye.	[37]
	4-amino N, N diethyl-meta-toluamide (DEET-NH ₂), Chitosan	Diazotized modified DEET (DEET-NH ₂) was prepared using HCl and NaNO ₂ . Chitosan solution (1%) was prepared and cotton fabric was padded with this solution bind chitosan with cotton fabric. Chitosan used as a coupler and reacted with DEET-NH ₂ obtain polymeric dyed cotton fabric.	[93]
Novel Acid Dye	ethyl anthranilate (ethyl 2-aminobenzoate), H-acid (4-Amino-5-hydroxy-2,7-naphthalenedi-sulfonic acid).	Diazonium salt was produced from ethyl 2-aminobenzoate, hydrochloric acid and sodium nitrite which later on reacted with H-acid at pH 7-8, 0 °C-5 °C. This coupling solution was heated to 60 °C and after the addition of sodium chloride the dye precipitated.	[2]
Novel Basic dye	Ethyl anthranilate (EA), imidazole	EA was reacted with Hydrochloric acid and sodium nitrite to produce diazonium salt solution which later on added to imidazole	[16]

Table 12. (Continued.)

Dyes	Major ingredients	Synthesis process	References
		solution to form Ethyl (E)-2-((1H-imidazole-2-yl) diazenyl) benzoate (I). Fine powder of I was reacted with Dimethyl sulfate and through quaternization E)-2-((2-(Ethoxycarbonyl) phenyl) diazenyl)-1,3-dimethyl-1H-imidazole-3-ium; the basic dye was formulated.	

microcapsules in electrospinning processes to fabricate repellent fibres and nanofibers [28, 29]. Few researchers employed nanoencapsulation technique [3] whereas others followed the microencapsulation technique.

Microencapsulation via Core Sheath (core–shell) provides a powerful method for incorporating active functions directly into textiles, while maintaining wearability, wash durability, and controlled release properties. These properties are highly relevant for mosquito protective and mosquito-sensing fabrics. Microencapsulation can be achieved by designing core-sheath structures in which the active payload is contained within a protective core, and the sheath controls diffusion. Majd *et al* demonstrated this principle using pressurised spinning and coaxial fibre formation: Hydrophilic and Hydrophobic drugs were encapsulated within polyvinylpyrrolidone (core) and ethyl cellulose (sheath). When compared to mixed fibre, this results in prolonged and adjustable release [96]. Similarly, tetracycline hydrochloride [97] and natural extracts such as garlic [98] have been encased in core-sheath designs. These findings confirm that core sheath Microencapsulation is a valid technique for producing functional textiles in which repellents or sensing agents can be protected and released in a controlled manner. Thus, core sheath Microencapsulation for textiles can be used in two methods to detect and control mosquitoes. Firstly, the repellents (Essential oil, DEET) can be delivered in a triggered manner with the shell controlling diffusion and shielding the core from abrasion and washing. Secondly, the Core sheath can act as functional sensor elements by encapsulating chemo-chromic dyes, or as nanoparticles in the core that change the optical properties on exposure to mosquito-associated volatiles or physical contact, by producing a localized sensor integrated with fabric [99].

Encapsulation technique for mosquito repellency has been shown in figure 7 and briefly discussed in table 14. The outcomes were stated in table 15 with their encapsulation characterization and functional properties.

Different researchers have undertaken various technique to prepare the micro capsule and among the reported works following three major techniques have been found to draw most of the attention:

4.2.1. Complex coacervation process

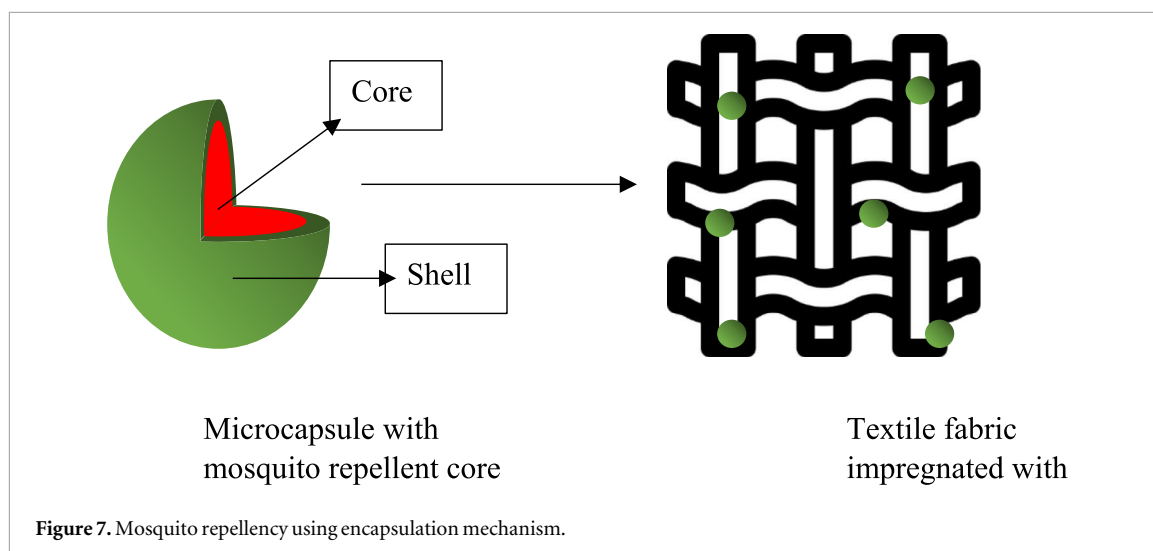
One popular microencapsulation method for water-insoluble compounds is the coacervation method, which entails distributing active chemicals in an aqueous environment using a high shear mixer [62]. In an attempt of complex coacervation process Place *et al* combined 9 mL of picaridin, 1.5 ml of Sodium dodecyl sulfate (SDS), and 10.5 ml of 1% Bovine serum albumin (BSA) in TRIS buffer followed by emulsification for one minute at 35,000 rpm. In order to cause complex coacervation, 24 mL of 2% PHMB was added to TRIS while stirring. This was followed by the addition of 90 μ l of 5% glutaraldehyde (GA) solution and another hour of stirring. The reaction was quenched in TRIS using 50 milliliters of 0.1% polyethyleneimine (PEI). After separating the MCs, the supernatant was extracted, and 30% ethanol was used to eliminate any unencapsulated picaridin [21]. Complex coacervation was also used by Tariq *et al* in their study to achieve microencapsulation, where they took 12.5% w/v gum Arabic in solution I, while 12.5% w/v gelatin was present in solution II. Solution II was added after Solution I had been combined with distilled water and peppermint oil. To improve coacervation, 10% acetic acid was added to the pH, and the emulsion was agitated while distilled water was added. For crosslinking, 25% glutaraldehyde was added, and the mixture was agitated for 30 min at 250 rpm while being kept below 10 °C. In order to create microcapsules, the finished emulsion was kept at or below 10 °C for 8 to 9 h in a separating funnel [101].

4.2.2. Emulsion extrusion

Murtaza *et al* utilized the emulsion extrusion method for microencapsulation of essential oil components. A 2% sodium alginate solution is prepared and degassed. Essential oil components are then homogenized with this solution until the desired loading is achieved. A 0.5% calcium chloride solution acts as a hardening agent.

Table 13. Dye characterization methods, their functional properties and outcomes.

Textile type	Characterization	Functional property	Outcome	References
Nylon	FTIR, HNMR spectroscopy	Mosquito-repellent	Good mosquito repellency; Good fastness properties like light, wash and rubbing.	[65]
Cotton	FTIR, Thermogravimetric analysis	Mosquito-repellent, antibacterial and UV protective	Mosquito repellent (100%), excellent UV protection, and antibacterial activity > 87%; durable antibacterial activity and mosquito repellency after ten washes.	[2]
Cotton	FTIR spectrometer, EDX analysis	Mosquito Repellent, Antibacterial, Anti-oxidant and UV Protective	Mosquito repellent (100%), excellent UV protection (UPF>50), antibacterial activity > 94% and antioxidant activity (>87%); durable antibacterial activity and mosquito repellency after 20 washes.	[79]
Polyester	FTIR, HNMR, UV spectroscopy, mass spectroscopy, and elemental analysis	Mosquito-repellent, antibacterial and UV protective	Mosquito repellent (100%), excellent UV protection (UPF>124), antibacterial activity > 93%, antioxidant activity with zero algal toxicity; durable mosquito repellency after 20 washes.	[67]
Polyester	FTIR, HNMR, MALDI-MS, CHN analyser, and UV-vis spectroscopy	Mosquito-repellent, antibacterial and UV protective	Mosquito repellent (100%), excellent UV protection, antibacterial activity > 94%.	[1]
Cotton	Bruker D8 x-ray diffractometer, HORIBA SZ-100 particle size analyser, FTIR spectral analysis, SEM Phytochemical analysis	Mosquito-repellent Mosquito repellent, Anti-bacterial	10% calcinated (pre and post) nanoparticles showed high mosquito-repellent efficacy even after 10 wash cycles; also had commercial viability Repels insects (90%), offers strong aroma (72%), and exhibits antibacterial properties (100; Natural dye yields light yellow with good fastness.	[33]
Cotton	FTIR, HNMR, CNMR (Carbon-13 NMR, CHN analyzer, and UV-vis spectroscopy.	Mosquito Repellent and UV protection	The dyed fabrics exhibited excellent mosquito repellency while maintaining strong overall fastness properties such as light, wash, and rubbing.	[37]
Nylon	FTIR, HNMR, CNMR, and CHN analysis	Mosquito-repellent and UV-protective	The dyed fabrics achieved complete mosquito repellency (100%) and provided outstanding UV protection.	[2]
Acrylic	FTIR, EDX, TGA, XRD and SEM	Mosquito repellent, antibacterial and UV protective	The dyed fabrics achieved complete mosquito repellency (100%); 97.2% repellency after 20 wash cycles.	[16]
Cotton	FTIR, HNMR, CHN analyser, UV-vis spectroscopy, and thermogravimetric analysis (TGA)	Mosquito repellency, and UV protection	The dyed cotton exhibited complete mosquito repellency (100%) with good durability, along with significant antibacterial activity (>78%) and good to very good UV protection.	[93]
Nylon	FTIR, HNMR spectroscopy	Mosquito-repellent	The dyed fabrics achieved complete mosquito repellency (100%) and provided outstanding UV protection.	[92]



The mixture is extruded into the calcium chloride solution, forming microcapsules. After 20 min of hardening, the microcapsules are filtered, washed, and dried, resulting in encapsulated essential oil components [25].

4.2.3. Interfacial deposition of pre-formed polymer

On the other hand, Cinnamaldehyde-loaded lipid-core nano capsules (Cin-LNCs) were synthesized via modified interfacial deposition of pre-formed polymer by Kamari *et al*. An aqueous solution of polysorbate 80 surfactant was gradually supplemented with an organic phase made up of Poly(ϵ -caprolactone), capric/caprylic triglycerides, span 60 surfactants, and cinnamaldehyde dissolved in acetone. Acetone was stirred and then evaporated under low pressure to produce a suspension. A 1 mg ml^{-1} concentration of cinnamaldehyde was obtained during evaporation to 10 ml. The mixture was kept at room temperature in amber flasks. Cinnamaldehyde can be precisely encapsulated using this technique in lipid-core nano capsules, which may provide enhanced stability and controlled release characteristics for a range of uses [27, 39].

4.3. Micro and nano emulsion

Essential oils (EOs) are typically derived from plants and are aromatic compounds. A number of EO chemicals are volatile and sensitive to oxygen and light. The functional and physicochemical properties of essential oils can be maintained through microemulsification, leading to a more durable product. Blend of Litsea-lemon essential oil (EO) with oil-in-water (o/w) ratio of 1:2, microemulsions has been prepared by mixing the blend of EO (30%) with 0.1% solution of sodium alginate and blending for five minutes at 8000 rev/min. Subsequently, chitosan solution of 1% was introduced. After a further hour of blending at same speed, addition of 0.1% calcium chloride solution was done drop by drop. Subsequently, all microemulsions were allowed to cure by being stored at room temperature for 24 h to facilitate elastic recovery. They were then kept at 40°C for an equal duration to aid in consolidating the micro-assembly crosslinked polyelectrolyte. Samples of knitted polyester and bleached cotton fabric were scoured for 30 min at 60°C using 2 g l^{-1} of the Ultravon PL (non-ionic surfactant). Subsequently, the surfactant was eliminated through washing. The cloth was then immersed in a microemulsion for 15 min following sterilization at 160°C for two hours. Samples of soaked fabric were processed using a lab at 35 kg/cm^2 pressure and a speed of 1 m per min, then soaked again and cushioned. Unless specified, every test was performed on fabric recently treated, left to dry at room temperature for 24 h [85].

The pad dry cure method used in microencapsulation and nanoencapsulation techniques presents a challenge as volatile oils cannot withstand high temperatures when applied to fabric, resulting in significant oil loss during processing. This necessitates higher concentrations of essential oils. Moreover, traditional processes have a detrimental impact on the texture of the processed material. An innovative method has been developed for modifying textile fibers that can be implemented at room temperature. Layer-by-layer deposition (LLB) is a method that enables polymer-based thin films to be applied onto a fabric; these layers are called polyelectrolyte multilayers (PEM). A substrate can be used to create thin polyelectrolyte films by immersing it in solutions containing both positively and negatively charged polyelectrolytes alternately, then washing it with water. One PEM had been deposited by repeating this process. Cymbopogon flexuosus (CF) oil was formulated into a nanoemulsion and applied to the fabric. Employing oil as a nanoemulsion through the LBL approach reduces the active component loading and helps to form on the substrate an even layer at the nano level. Homogeneous

Table 14. Encapsulation techniques of mosquito repellent agents to textile materials.

Core material	Shell/Wall	Encapsulation method	Repellency type	Textile type	Impregnation method	References
Frankincense oil	Chitosan	—	Combined	Cotton	Pad-dry Method	[17]
Picaridin	polyhexamethylene biguanide (PHMB)	Complex Coacervation	Synthetic	Cotton	Immersion- drying	[21]
Citriodiol	Aminoplaste	Interfacial Deposition of Pre-formed Polymer	Synthetic	Cotton	Pad- dry- Cure Method	[100]
	Gelatin and Arabic gum Ethylcellulose	Complex coacervation	Natural	Cotton-Polyester Blend	Impregnation, coating and printing	[94] [38]
Lemongrass Oil	Gum Acacia	—	Natural	Cotton	Pad- dry- Cure Method	[84]
Lemon oil and metal nano particles	Pectin and gelatine	Mechanical homogenizing mixing method	Combined	Cotton and Wool	Pad- dry-Packing	[26]
Peppermint Oils	Gum Arabic	Complex Coacervation process	Natural	PC blend	Pad -Dry -Cure Method	[101]
Citronella oil	Gum Arabic	Complex Coacervation process	Natural	Cotton	Pad- Dry -Cure Method	[57]
	Gelatin				Immersion- drying	[102]
	Gelatin and Arabic gum				Pad- Dry -Cure Method	[94]
Limonene and permethrin	Ethyl cellulose	Complex Coacervation process	Combined	Cotton	Pad -Dry -Cure Method	[62]
Cinnamaldehyde	poly(ϵ -caprolactone) nanocapsules	Interfacial Deposition of Pre-formed Polymer Method	Combined	Cotton fabric and Polyester fabric	Spray gun	[39]
Betel essential oil	Poly(ϵ -caprolactone) nanocapsules	Interfacial Deposition of Pre-formed Polymer Method	Combined	Cotton fabric and Polyester fabric	Spray gun	[27]
Eucalyptus oil	Moringa gum, Arabic gum	Complex Coacervation process	Natural	Cotton-Polyester Blend	Pad -Dry -Cure Method	[80]
Cinnamon bark oil	Chitosan-gelatin	Emulsion extrusion	Natural	Linen	Pad-dry Method	[83]

Table 15. Encapsulation characterization, their functional properties and outcomes.

Characterization	Functional properties	Outcomes	References
SEM, FTIR, TGA, and EDX	Mosquito-repellent, Anti-bacterial, Antioxidant, and Flame-retardant	100% mosquito repellency (100%), More than 66% antioxidant activity, 88.69% and 94.5% antibacterial activity against <i>E. coli</i> and <i>S. aureus</i> respectively, and LOI of 24 with a pleasant aroma	[17]
FTIR	Mosquito repellent, Anti-bacterial, Anti-fungal	According to GC data, picaridin loading levels are ten times higher than what is needed to repel mosquitoes; MCs can be employed to give fabric the antibacterial function they possess even at dilutions of 10 and 100. They also endow textiles with antimicrobial characteristics	[21]
—	Mosquito repellent	Upon completion, the textiles exhibited 96% repellent activity through direct application and 94% activity by microencapsulation. While the direct application method demonstrated mosquito repellent action for just ten washes, the microencapsulation method shown good activity for up to thirty washes	[42]
SEM, Raman spectroscopy	Mosquito repellent	According to the results, both methods have the potential to produce effective textile repellents that might be used for disease prevention and mosquito control	[28]
SEM, Gas chromatography	Mosquito repellent	When microcapsules are added to cotton fabrics, treated cellulose sheets exhibit increased mosquito repellency, which lowers the amount of mosquito bites that occur to those who sleep in treated bed clothes. As a general assessment, we note that the repellence seen was believed to be fairly effective.	[84]
Optical microscopy; Scanning electron microscopy;	Mosquito repellent	The percentage of mosquito repellency was approximately 90%; this eco-friendly approach resulted in a mere 28.5% decline in mosquito repellency even after 30 washings.	[101]
—	Mosquito repellent	PC fabric coated with 6% microencapsulated peppermint oil demonstrated 95.3% mosquito repellency at zero wash, and after 30 washes, the repellency was 85.8%, confirming the completed fabric's durability.	[59]
Optical microscopy (OM), Scanning electron microscopy, Gas chromatography	Mosquito repellent	The microencapsulated DEET formulation consistently repelled mosquitoes over 6 months, maintaining efficacy, blood-feeding inhibition, and mosquito fatality rates. In contrast, conventional DEET repellency decreased over time	[57]
Gas chromatography-mass spectrometry (GC-MS); FT-IR; SEM	Mosquito Repellent	Assuring a repellent effect higher than 90% for three weeks;	[25]
Laser diffraction analysis, FTIR, SEM	Mosquito Repellent	Encapsulated finishes shown a much higher repellency (>90%), making these textiles resistant to mosquitoes the best substitutes for synthetic repellent. They are also a safer option than lotions and ointments, which can cause a variety of skin issues when applied topically.	[62]
Particle size distribution, SEM	Mosquito repellent	Mosquitoes avoided treated fabrics, and mortality rates for permethrin and limonene were 41% and 54%, respectively. After 20 wash cycles, the textiles retained their repellency, although efficacy declined with increased washing	[103]
FTIR, TGA	Mosquito repellent	After being finished with 15% (solid in water) citronella oil microcapsules, the fabric sample showed 90% mosquito repellency at zero wash, and after thirty washes, the fabric had 80% mosquito repellency, indicating that it will remain durable as finished.	[39]

Table 15. (Continued.)

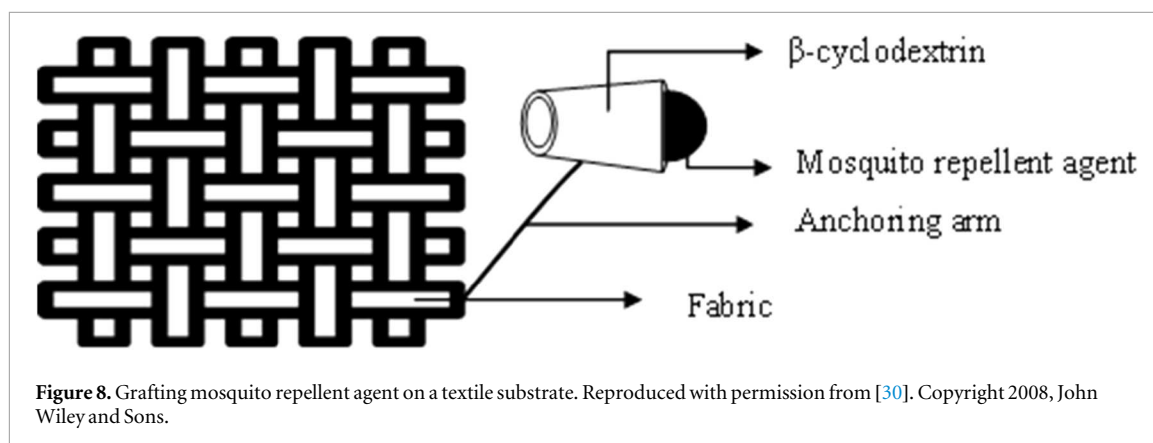
Characterization	Functional properties	Outcomes	References
SEM	Mosquito repellent	In field studies, mosquito net treated with Cin-LNC formulation demonstrated 100% repellency against mosquitoes throughout both day and nighttime hours. A human volunteer's skin irritation test revealed no signs of apparent irritation.	[29]
UV-Visible spectrophotometr, FTIR, SEM	Mosquito repellent	Compared to monolithic ones, core-enriched fibrous mats showed a longer repellency time. Core-enriched mats with the highest CD content in the core (CD/EC 7:10) and the lowest CD content in the shell (CD/EC 5:10), which were laid for 36 h, showed 100% repellency for 34 days as an example of this behavior.	[27]
—	Mosquito repellent, Antibacterial, Fragrance	Higher antimicrobial activity; higher mosquito repellent activity; and higher UPF values are obtained by treating fabrics with AgNPs (5%) encapsulated in gelatin biopolymer, TiO ₂ NPs (5%) encapsulated in pectin biopolymer, and ZnONPs (5%) encapsulated in gelatin biopolymer.	[26]
SEM, FTIR, TGA, Particle size analyzer	Mosquito repellent	Without applying any liquid bases to their skin, this final fabric's ability to repel mosquitoes will allow people stay protected from them for extended periods of time.	[80]
SEM, EDX and FTIR	Mosquito repellent, Antibacterial, Anti-oxidant, Fragrance	The chitosan-gelatin shell encapsulating cinnamon bark oil core achieved durable antibacterial, mosquito repellent (up to 100% efficacy for 20 washes), antioxidant, and fragrant properties in finished linen.	[83]

deposition on the substrate is made easier by the small droplet size, enhancing durability while maintaining the texture of the cloth. 500 ml of nanoemulsion was prepared by combining oil of CF (5ml), span 80 (2.2ml), and tween 80 (2.8 ml), using a surfactant to oil ratio of 1:1. The solution was homogenized at 1500 RPM for thirty minutes with a homogenizer. Two solutions of polyelectrolyte have been produced: one with 0.1% cationic polyelectrolyte, RF 8220 adjusted to pH 7, and the other with 0.1% anionic polyelectrolyte, RF 8162 adjusted to pH 5. The anionic polyelectrolyte solution was mixed with a specific volume of CF oil nanoemulsion. To remove the molecules of cationic polyelectrolyte that were loosely bound, a net fabric made with nylon substrate was first soaked in the solution of cationic polyelectrolyte for two minutes and then rinsed with distilled water. To eliminate any weakly bound anionic polyelectrolyte molecules, the fabric was rinsed in distilled water following anionic polyelectrolyte and nanoemulsion of CF oil were soaked for two minutes. This process was referred to as One Polyelectrolyte Multilayer (PEM). Depending on the required number of PEMs to be applied, the cloth is once again soaked in the solution of cationic polyelectrolyte, and repeated as necessary [81].

4.4. Grafting

The method involves immersing room-temperature cotton samples, measuring 4 cm by 4 cm, in an aqueous solution comprising 150 g l⁻¹ of CDMCT (Monochlorotriazinyl- β -cyclodextrin) and 150 g l⁻¹ of sodium carbonate (figure 8). Squeezing is used to get rid of the extra solution after five minutes of magnetic stirring. The impregnated samples were exposed to dry heat at 130 °C for 15 min in an oven to stop CDMCT from reacting with moisture. Any unreacted CDMCT was then rinsed with demineralized water. After that, the samples were kept in a dry box with constant ambient temperature and 56% relative humidity. DEET and permethrin were dissolved with a ratio of 7:3 of water: methanol to achieve a concentration of approximately 0.1 M for inclusion. The cotton samples treated with CDMCT are submerged in this emulsion and stirred magnetically for 12 h at room temperature. Subsequently, the samples are washed for 5 h by tap water, demineralized water, and a 4:1 ratio of water: methanol to remove any non-included chemicals that might have adhered onto the fabric surface [30].

The process of permanently grafting of MCT- β -CD involved immersing 25 × 25 cotton samples in a solution containing MCT- β -CD and 20 g l⁻¹ of sodium carbonate at room temperature for five minutes with



magnetic stirring. Subsequently, the samples underwent 100% compression using a pad mangle. To minimize MCT- β -CD's reactivity to moisture, the treated sample was heated to 130 °C for fifteen minutes in an oven. After treatment, the samples were dried in a standard laboratory setting after being rinsed with water to eliminate any unreacted substance [73].

Hebeish A. *et al* conducted experiments to enhance cotton fabric's insect-repelling properties by incorporating efficient insecticides (permethrin, bio allethrin) into the molecular structure of the textile material. Chemical modification involved grafting utilizing fast electron beam irradiation and either glycidyl methacrylate (GMA) alone or in conjunction with β -cyclodextrin (β -CD). Duck cotton fabrics were purified and treated with GMA monomer or a GMA monomer and β -CD combination or GMA monomers with permethrin combination in a finish bath for 1 h, followed by irradiation. Washing and drying of the fabric were done after treatment. For grafting with β -CD, grafted cotton fabrics were reacted with a β -CD solution at 80 °C containing NaCl and NaOH. After grafting of β -CD, repellents for insects were added by immersing cotton-g-GMA/ β -CD fabric in a blend containing permethrin dissolved in distilled water and ethanol to form inclusion complexes for 24 h at room temperature. Following an ethanol and distilled water rinse, the treated fabric was allowed to air dry. Irradiation was conducted using electron beam accelerators at specific energy parameters. The fabric underwent washing to remove non-reacted materials, ensuring purity. The inclusion complex formation enhanced the fabric's ability to hold insect-repelling agents [72].

4.5. Electro-spinning

In their work, Ciera *et al* [27] employed the electrospinning technique to confer mosquito repellency. The spinning solution was prepared by dissolving the required amount of PVA in 20 ml of distilled water to achieve an 8 wt% solution. Following gentle stirring with a magnetic stirrer for 6 h at room temperature (21 ± 1 °C), the solution was utilized for electrospinning the microcapsules without further modifications. However, for emulsion electro-spinning, varying concentrations (0, 2, 4, 6, 8, 10, 12, 14, and 16 wt%) of repellents were added to the prepared PVA solution. Subsequently, the solutions were sonicated for 30 min using a Branson 1510 Sonicator (USA) to ensure uniform emulsion, then immediately electrospun to prevent phase separation. The resulting solutions were electrospun into nanofibers utilizing a mono-nozzle electrospinning set-up.

Furthermore, in a complementary investigation, Muñoz *et al* [29] examined the effectiveness of incorporating essential oils into electrospun nanofibers for mosquito repellency. Their study involved using magnetic stirring; 10% (w/v) EC solutions were made in both Et and Et/DMAc mixtures (40:60 and 30:70 v/v). Conditions for using a YFLOW 2.2.D-350 electrospinning device were as follows: room temperature with relative humidity below 50%, needle-to-collector distance of 10-15 cm, and an applied voltage of 15-20 kV. Over two hours, mats were gathered onto polyester cloth. Two techniques were used to manufacture CD-loaded EC mats in the trials that followed. 10% (w/v) EC solutions with CD ranging from 10%-70% (w/w with regard to EC) were used to create monolithic nanofibers. As an alternative, a coaxial nozzle was used to create core-enriched nanofibers (C1 and C2). Whereas C2 had ratios of 5:10 in the shell and 7:10 in the core, C1 had CD/EC at a 7:10 ratio in the core. The samples were placed in a desiccator and vacuum-dried for an entire night at room temperature.

4.6. Coating

Indrajit *et al* synthesized mosquito repellent polyurethane (Mos PU) by stirring polycaprolactone diol 2000 (PCL) and citric acid-based functional polyol (CFP) under vacuum at 80 °C for 1 h to eliminate moisture, with a nitrogen gas blanket maintaining an oxidation-free atmosphere. Methylene diphenyl diisocyanate (MDI) dissolved in dimethyl formamide (DMF) solvent was added in a 1.2:1 NCO/OH ratio at 50 °C, followed by a temperature increase to 80 °C at a rate of 2 °C min⁻¹. Dibutyltin dilaurate catalyst was introduced, and the

reaction continued until a constant NCO value was attained, indicating prepolymer stability. After adding butanediol to increase molecular weight, DMF was added for viscosity reduction, and ethyl anthranilate was included for mosquito repellency. Ionic bond formation between polymer carboxylic acid and ethyl anthranilate amine occurred at 80 °C for 30 min. Low-temperature amidation was carried out for an hour with 5-Methoxy-2-iodophenyl boronic acid (MIBA) catalyst addition. The resulting Mos PU was used directly for coating cotton fabric using a knife-in-air coating machine. Coated fabric drying occurred at 120 °C for 4 min, with intermediate drying between coats to vary the Mos PU add-on levels [40].

4.7. Fabric with applied DC voltage

A different type of approach for mosquito repellency was applied on fabric in which a direct current (DC) extra low voltage field has been applied, and this technique is named biomimetic mosquito-repelling technology. The components of mosquito-repellent fabric (MRC) consist of two layers of electrically isolated conductive knits on the top and bottom, with one layer of fiberglass woven mesh in the center. Here, the top and bottom layers were attached using 3M 77TM Multipurpose Adhesive. The morphometrics of the *Aedes aegypti* head were utilized in MRC's physical structure design. A groundbreaking three-dimensional textile, consisting of 33% fiberglass, 66% PVC, and 1% other components, has been built using the structure of the mosquito head as a model. The three-dimensional design of the MRC was a crucial component that enabled mosquitoes to probe through the layered fabric and connect the two conducting layers, encompassing the size and thickness of the pore. A bioassay system named *in vitro* feeding utilized for repellency evaluation, revealing a decrease in blood feeding by mosquitoes when voltage rose from 0 volts. At 10 volts, inhibition of blood feeding reached 97.8%, and at 15 volts, it reached 100% [104].

4.8. Fabric with thermophysiological properties

Concerns over the health consequences of wearing clothing treated with pesticides are growing, a model (mathematical) based on textile structure has been proposed for obstacles that repel *Aedes aegypti* mosquitoes (100% mosquito bite-resistance) without insecticides in the fabric. A study of biting behavior and mosquito morphometrics was used in the development of the model. Knitted fabrics, precision polypropylene plates, and woven filter fabrics were utilized for model validation. The model's predictions were then used to create prototype knitted clothes and materials that would shield wearers from mosquito bites. Next, this model has been utilized to develop wearable and comfortable materials for clothing. Comfort testing demonstrated the superior thermophysiological properties of the clothing. In comparison to the insecticide (permethrin)-treated cloth, this provided three times greater bite resistance, which was measured using an *in vitro* feeding/bioassay system [43].

5. Application method

5.1. Dyeing

Singh *et al* and Teli *et al* followed the cold brand and hot brand reactive dyeing methods, respectively, to dye the Nylon fabric with synthesized dye in different shades (1%-5%) [92], keeping the material to liquor ratio (M: L) to 1:10 [92] to 1: 20 [65]. Singh *et al* dyed at 40 °C temperature for 1 h followed by cold wash and soaping with 1 g l⁻¹ soaping agent for 10 min at 60 °C whereas Teli *et al* started dyeing at 40 °C adding the dye, ammonium sulphate (1%-2%) and fabric, but raised the temperature to 80 and continued dyeing for 30 min followed by the addition of alkali, 1% on the weight of fabric (o.w.f) and continued the dyeing for additional 30 min. Finally, washing the materials with 2 g l⁻¹ non-ionic soap and soda ash at 80 °C-85 °C followed by a cold wash [65, 92]. On the other hand, Singh *et al* in their other two works, where they synthesized novel disperse dyes, adopted the disperse dyeing method to dye polyester fabrics in a magnetic dyeing machine at 130 °C for 1h with M: L of 1:20, maintaining a pH of 4.5–5. The pH was maintained using a buffer solution of acetic acid and sodium acetate (acetate buffer). At the end of the dyeing, cold wash, reduction clearing, and neutralization were carried out. For reduction clearing 2 g l⁻¹ of sodium hydroxide and sodium dithionite were used [1, 67].

In the case of novel azo dyeing three of the works were carried out by Singh *et al* [2, 79, 93] where they used natural materials to naphtholate cotton fabric which were later on reacted with diazonium salt (modified DEET) to develop the color in *in situ* process but in the work of Teli *et al* [37], they used three naphthol to treat cotton fabric before coupling reaction. At first, Singh *et al* diazotized the modified DEET (DEET-NH₂) to produce diazotized base solution, by dissolving it in a mixture of water and HCl at 0 °C-5 °C temperature, followed by the addition of sodium nitrite, and carried out the process for 1.5–2 h. The diazotized solution was neutralized using an acetate buffer. On the other hand, henna extracts, catechu extract were dissolved in sodium hydroxide at 90 °C for one hour and used in the exhaustion to the cotton fabric in a rota dyer machine at a time-temperature profile similar to the extraction and followed by padding in a padding mangle. This naphtholated

fabric was immediately treated with diazotized base solution at 40 °C for one hour in a rota dyer machine for the *in situ* coupling reaction, which developed the azoic dye. The dyed fabric was treated with HCl, followed by soaping at 60 °C to get the final product [2]. Singh *et al* in their other study used Ethyl Anthranilate (EA) replacing DEET, although they followed a similar pattern of Diazotization of EA > Exhaustion of Cotton fabric using coupling agent (Terminalia chebula extract) > Coupling with Diazotized EA to develop the final color [79]. A similar approach was seen by the same set of researchers, where they used chitosan as a coupler and reacted the chitosan-bound cotton with diazotized base (DEET-NH₂) to develop the polymeric dye in an *in situ* synthesis process [93]. Although Singh *et al* used a natural source for the coupler, Teli *et al* used three naphthols named Naptol ASBS, Naphthol ASG, and Naphthol ASBO as coupler, which later on reacted with base solution (DEET-NH₂) [37].

Singh *et al* in their other attempts, produced novel acid dye [2] and basic dye [16], which followed their generic dyeing method of acid dyeing and basic dyeing, respectively. In the former case, nylon dyeing was carried out in an Infra-Red laboratory dyeing machine (IRLab Dyeing m/c) with an M: L of 1:10 for one hour at 90 °C, maintaining a pH of 3-4, followed by a 5-minute cold wash at room temperature and 20 min hot wash at 60 °C. In the latter case, Acrylic dyeing was carried out in an IRLab Dyeing m/c at 95 °C for one hour in a similar pH and followed by similar post-dyeing washes [16]. On the other hand, Endris *et al* adopted a dyeing method with a similar extract (Eucalyptus leaves) where dyeing involved pre-soaking samples in dye solutions with varying concentrations and temperatures, followed by simultaneous mordanting and dyeing through padding. A two-bowl padding mangle was used with an 80% wet pick-up, followed by drying. Optimization was achieved using Box-Behnken design, reducing experimental trials while exploring parameter effects efficiently [36].

5.2. Printing

An approach undertaken by Kantheti *et al* [33] where they synthesized nanoparticles from fresh eucalyptus using a green synthesis method, where they used TiO₂ as a precursor. The rinsed leaves were boiled at 60 °C for 1–2 h at a 1:5 material to liquor ratio, followed by filtering with Whatman no 41. Filter paper. 1 molarity of precursor was dissolved in 100mL of distilled water and stirred on a magnetic stirrer for one hour. Then 40 mL of leave extract was slowly added and stirred for 4 h, followed by drying in a hot air oven and calcinated in a muffle furnace at 200 °C for 2 h. The print paste was prepared using a dye and gum (4:3) mixture, followed by the addition of copper sulphate (mordant, 0.8 g/100 g). The concentration of the nanoparticles was kept at 5% and 10% and both pre- and post-calcinated forms were used. The prepared print paste was applied to the fabric sample by printing. It's noteworthy for better dye fixation sample fabric was pre-treated with myrobalan powder (20 g/100 g fabric) and post-treated by shade drying > steaming at 100 °C > Steeping (5% NaCl) > rinsing (neutral detergent) > and shade drying.

Microcapsules (40 g) were incorporated into the printing paste and directly printed onto the textile. The printing process utilized the largest porous template, glitter, and pigment printing paste (994 g), with the printing material thickened using alginate. Drying and fixing were done at 120 °C for 3 min [38].

5.3. Pad-dry-cure

A dispersion was formulated using 100 g l⁻¹ microcapsules and 30 g l⁻¹ binder, followed by padding of cotton fabric using a padding mangle, which was later dried for 5 min at 80 °C [17]. In a another investigation by Place *et al* [21], Nylon-Cotton (NyCo) fabric was cut into 1' × 1' pieces and immersed in a Falcon tube filled with 4.5 mL of deionized water per swatch. Following this, 0.5 mL of MCs was added per swatch, creating a tenfold dilution. The tube was vortexed for an hour. After completion, the fabric swatches were gently removed, patted dry with a paper towel, and left to air-dry overnight. On the other hand, Bonet-Aracil *et al* [100] employed a horizontal foulard for padding, where a pickup of roughly 89%–90% was obtained, which ensured effective absorption of the bath solution. The binder was then cured using hot air, which also made it easier for the microcapsules to stick to the fiber surface.

Vinayagamoorthy *et al* [84] coated a lemongrass extracts capsule mixture on the fabric using a pad-dry-cure method, where binder compounds like polyurethane and acrylic were used to finalize this agent by fixing the microcapsule to the fabric's surface and enabling the last lingering effect. In this study, microcapsules were combined with an acrylic crosslinking agent at 15% V/V to create a finishing solution, with the remaining amount filled with softener (Perisoft Nano, Bayer). A pneumatic padding mangle was used to immerse cotton knit fabric in this solution. The cloth was then squeezed and dried in an oven at 80 to 85 °C thereafter. In another study by Türkoğlu *et al* [62] insect repellent capsules (40 g l⁻¹) and an acrylic-based binder (50 g l⁻¹) were added to an application bath. 90% of the materials were wet pick-up after being impregnated in the bath and forced through the rollers. In a lab stenter, the fabrics underwent a single step of drying and fixing (7 min at 120 °C).

5.4. Spraying

In their study, Kamari *et al* [27, 39] investigated the interaction between Cin-LNCs and three fabric types: cotton, polyester, and tetron cotton. The concentrated Cin-LNC formulation was diluted with deionized water to 125 mg l^{-1} (1250 mg m^{-2}), a common dosage for protective garments. After spraying, the fabrics air-dried at room temperature. Meanwhile, Correa-Morales *et al* employed targeted indoor residual spraying (TIRS) against pyrethroid-resistant *Aedes aegypti*, per WHO guidelines. They combined bendiocarb (80% concentration) and pirimiphos-methyl (28.16% concentration) in 7.5 liters of water. Using a manual compression sprayer, they applied the mixture at flow rates of 580 ml min^{-1} and doses of 0.407 g AI/m^2 for bendiocarb and 0.955 g AI/m^2 for pirimiphos-methyl. Cone bioassays confirmed effective short-term mortality, suggesting these compounds as pyrethroid substitutes in resistance-prone areas. Both studies contribute insights into novel vector control strategies, crucial for combating insecticide resistance and enhancing public health outcomes [105].

5.5. Coating

The coating was applied through the conventional pad-dry-cure technique. A mini-padder regulated the solution pickup rate, while a mini-stenter handled the drying and curing process. The standard procedure involved pouring the coating solution into a $12'' \times 12'' \times 2''$ tray. A net cloth measuring 50 cm by 16 cm was then immersed in the mixture. To reduce excess liquid and maintain an 80% pickup rate, the wet net was transferred to the padding machine and pressed at two bars of pressure. The padded net was subsequently dried and cured for two minutes at 150°C in a stenter [82].

5.6. Immersion

In a study by Ap dos Santos *et al* [21] employed exhaustion method to apply microcapsule on 100% cotton white jersey knit fabric where 7g of fabric was pre-treated by washing it using ISO 105-C06 method A1S and then drying it in a Carbolite incubator for 90 min at 40°C . Samples were impregnated using a sub micro repellent solution at a ratio of 1:20 textile to solution after being conditioned for 24 h under typical textile conditions. The impregnated samples were then placed in a 200 ml stainless steel mug with a hermetic top and rotated for 30 min at $40 \pm 2 \text{ rpm}$ at 40°C . Samples were then centrifuged, cleaned, and baked for 120 min at 37°C to dry them out. In a different study by Ramya *et al* [42] submerged the fabric sample for half an hour at 50°C in the microcapsule solution. When it was done, the fabric was taken out, squeezed, dried for five minutes at 80°C , and then cured for two minutes at 120°C . A study conducted by Sariisik *et al* used a variety of techniques, including impregnation, coating, and printing, to incorporate microparticles into upholstery textiles. Chemical crosslinking made it easier for the microcapsules to adhere to the cloth fibers. Microcapsules were incorporated into the printing paste and then applied straight onto the textile material during the printing process. Alginate thickener for consistency, glitter template, and pigment printing paste were used in the process. Fabrics were treated in a Stenter for thirty seconds before to coating in order to guarantee smoothness. Using a squeegee, a waterproof acrylic coating polymer with microcapsules for further functionality was applied. An ideal capsule sample was squeezed between rollers and submerged in a solution bath during the impregnation process [38].

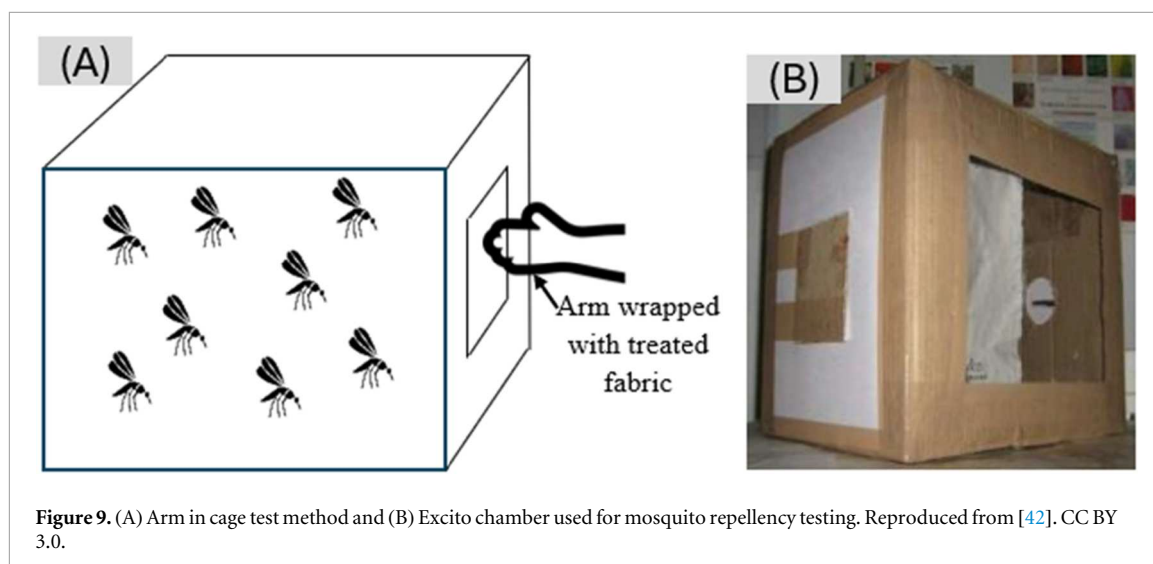
6. Evaluation of repellency

6.1. Cage test

To measure the repellency, Teli *et al* used a cage of $40 \text{ cm} \times 30 \text{ cm} \times 30 \text{ cm}$ [65], and Singh *et al* used a cage of $200 \text{ mm} \times 180 \text{ mm} \times 150 \text{ mm}$ [67] where the temperature and relative humidity (RH%) were maintained at $25 \pm 3^\circ\text{C}$ and $65 \pm 5\%$ respectively. A volunteer's arm was wrapped with treated and untreated fabrics and placed inside the cage for 30 min, where over a hundred local [37] or breaded [65] mosquitoes were already released (figure 9(A)). The test subjects reported any mosquito landings that occurred during the 30-minute exposure period of the sample to mosquitoes in the appropriate time intervals (after 2, 5, 10, 20, 30 min). At the end of the exposure, the number of landings was tallied and documented. The percentage decrease in the quantity of landings on the treated sample relative to the control sample was designated as the percentage of repellency using the following equation:

$$\text{Mosquito repellency(\%)} = \frac{x - y}{x} * 100$$

Where x and y are the number of mosquitoes that landed on the untreated and treated samples, respectively.



6.2. Excito chamber

WHOPES Excito Chamber test method is a modified conventional method where the two acrylic chambers of 30 cm × 30 cm × 30 cm with a middle exit portal that can be opened or closed as per requirement. 30 mosquitoes were released in chamber where treated fabrics were placed (figure 9(B)). The number of mosquitoes left the chamber and escaped to the other part, where untreated samples were placed was recorded after 30 min, and it was carried out four times. The mosquitoes later on stored in a breathable chamber with enough nutrition to observe their mortality. The efficiency was measured in percentage using the following equation:

$$\text{Efficiency of the mosquito repellent(\%)} = \frac{x + y}{x} \times 100$$

Where x and y are the number of mosquitoes escaped and died, respectively [33].

6.3. Tunnel test

The tunnel test, a laboratory device, facilitates the assessment of behavioral and toxicological responses in host-seeking mosquitoes exposed to treated materials. It precedes experimental hut trials to gather data on repellency, blood-feeding inhibition, and mortality. The equipment consists of a square glass cylinder divided into two sections by net-covered frame. One compartment houses a free-range guinea pig, while the other hosts 100 female anopheline mosquitoes released at sunset. Nine 1 cm holes in the netting allow mosquito entry. Mosquitoes found in each compartment—alive, dead, fed, or unfed—are counted the following morning. Delayed mortality is calculated by observing live mosquitoes exposed to sugar solution for up to 24 h. At six-month intervals, two replicate tunnel tests with 100 mosquitoes each are conducted on treated netting samples for each repellent formulation. These tests are vital for evaluating the efficacy of repellents and informing mosquito control strategies [59].

6.4. Cone bio assay

Four cones were prepared for conducting cone bioassays as per the guidelines of the World Health Organization (figure 10). The setup included a test fabric measuring 15 × 15 cm, covered by transparent cones measuring 13.5 cm in diameter and 18 cm in height, positioned at a 60-degree angle. Ten mosquitoes were introduced into each cone by sealing the narrow end with an untreated cotton cloth. The mosquitoes remained in contact with the test fabrics for three minutes. The mosquitoes tested were then removed from the cones and placed in a small, aspirator-style cage that is free of pesticides and maintained at 25 ± 2 °C with 50%–70% relative humidity for a 24-hour observation period. After 60 min and 24 h of observing the live and dead mosquitoes, the proportion of mosquito mortalities/knockdowns was calculated using the following formula.

% of Mosquito Mortality knockdown = (No of mosquitoes knocked over / Total no of mosquitoes introduced) × 100 [18].

6.5. Other bio assays

In another bioassay test, repellency tests were conducted using pre-mated 3–5-day-old *Aedes aegypti* females, starved for 6 h. Four 0.01 m² jersey knit fabric samples were employed: one untreated control and three treated with a submicrorepellent. An anesthetized adult female BALB/c mouse was positioned above each sample

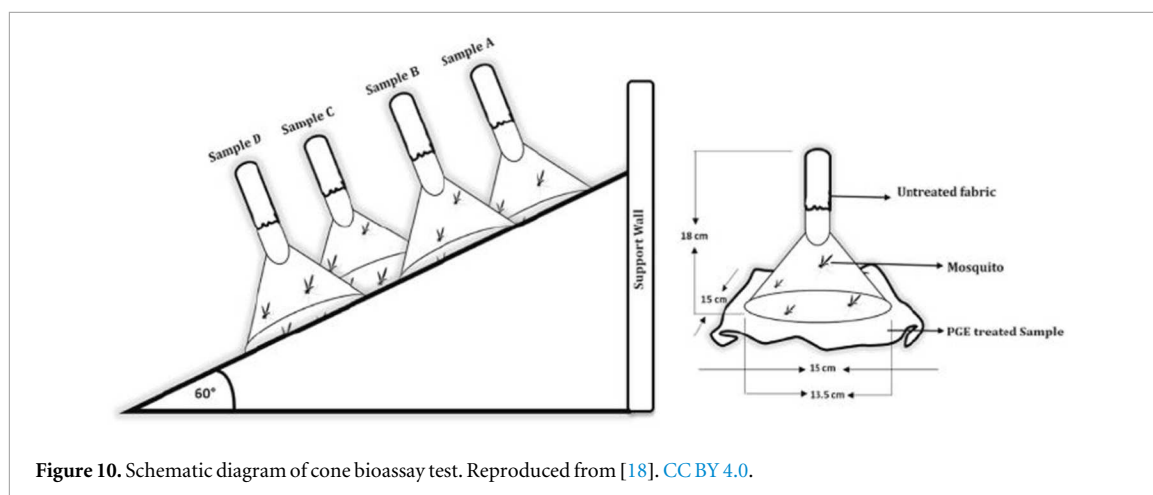


Figure 10. Schematic diagram of cone bioassay test. Reproduced from [18]. CC BY 4.0.

inside a 0.001 m^3 plastic cup covered with mosquito netting, housing 50 mosquitoes. Repellent activity was gauged by observing the mosquitoes' probing and biting behavior. Qualitative assessment of control and treated fabric efficacy was conducted after 72 h. Additionally, the fabric's ability to hinder blood-feeding behavior in female *Aedes aegypti* was evaluated by exposing a mouse to mosquitoes over control and treated fabric. While mosquitoes probed the untreated fabric, they refrained from approaching or biting the fabric treated with the submicrorepellent [3].

6.6. Glove's method

The WHO glove method was used to evaluate mosquito repellency. Two types of gloves - uncoated (UG) and coated (CG) - and three pairs of experimental participants - three experimenters and three observers - were required to carry out the experiments. Additionally, three cages with approximately 250 adult female *C. quinquefasciatus* that had not been fed human blood were prepared.

Prior to testing, each experimenter cleaned their two unworn UGs ten times. Subsequently, the experimenter extended their arm into the cage, maintaining it there for a minute while concealing their hands. An observer seated opposite the experimenter tallied the mosquitoes landing on the glove post-observation. Upon completion, the same experimenter repeated the test using a pair of CGs instead of UGs. Following these initial tests, the observer and experimenter switched roles, commencing a new round of testing. Each researcher conducted a total of six tests, spaced thirty minutes apart, recording the total mosquito landings for both UG and CG separately.

Using the following equation, the percentage of mosquito repellency was determined by dividing the total number of mosquitoes that land on a coated glove (MCG) by the number that land on an uncoated glove (MUG) [82].

$$\% \text{ in house mosquito repellency} = ((\text{MUG} - \text{MCG}) / \text{MUG}) \times 100.$$

6.7. Swiss tropical institute standard

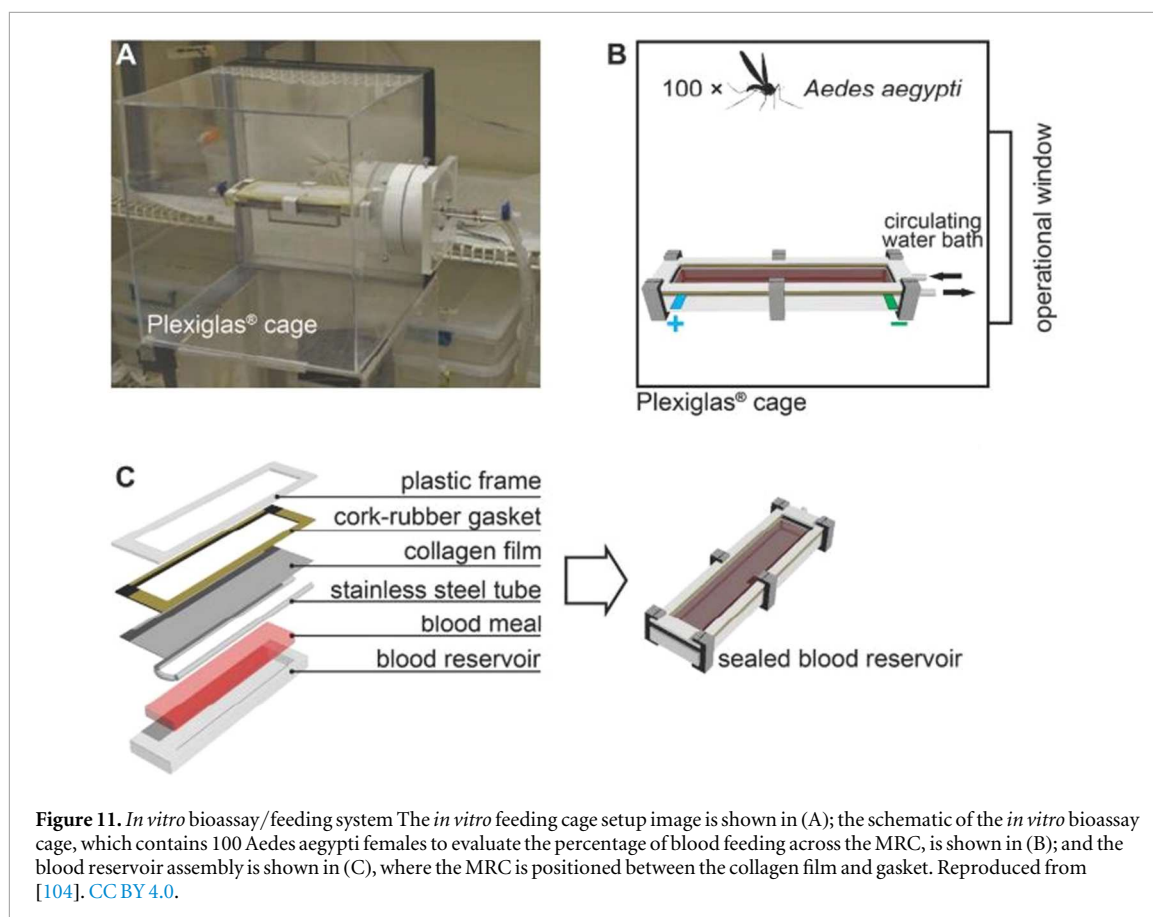
In the comparative test between tissue A and tissue B for mosquito repellency, a $30 \times 30 \times 30 \text{ cm}$ mosquito cage covered with gauze is utilized. A piece of tissue is placed atop the cage, with a bowl of water set on it as an attractant, measuring 65 cm^2 of warmed surface. 100 females *Aedes aegypti* mosquitoes populate the cage, and their landing on the tissue is recorded after 1 and 5 min across four independent counts. The reduction in mosquito landings after 5 min serves as the final efficacy metric. Separate mosquito populations are employed for each tissue test. Daily, the number of new mosquito bites on participants' skin is tallied to gauge repellency efficiency, calculated as the percentage reduction in bite count.

$$\% \text{Reduction} = \frac{x - y}{x + y} * 100$$

Where x No. of bites from an individual on the white sheet, y No. of bites from an individual on the sheet treated with microcapsules [100].

6.8. In vitro feeding

The feeding system comprises the mosquitoes' Plexiglas[®] cage (figure 11(A)), a blood reservoir (figure 11(C)), and a water bath that circulates to maintain the blood at a constant temperature of around $37 \text{ }^\circ\text{C}$ (figure 11(B)). The blood reservoir was inserted into the Plexiglas[®] cage through the operating window (figures 11(A), (B)),



which also served as a conduit for the power cables to the electrified cloth and the stainless-steel tubes used to circulate warm water. The collagen film was placed over the blood reservoir during testing, and the electrified cloth was placed on top of the collagen film (figure 11(C)). Mosquitoes are drawn to the surface by the heat and are served as counterfeit human skin by the membrane and blood. To feed on blood, they pass their proboscis through the collagen membrane and fabric. 100 *Aedes aegypti* females seeking hosts for their first oviposition cycle were used in each test. Blood from *Bos Taurus* cows was mixed with 0.2% wt/vol sodium citrate to prevent clotting. The blood was then stored in our laboratory at 4 °C in small aliquots at –80 °C until required, ensuring it did not freeze again [104].

6.9. Attractive blood-feeding device (ABFD)

A novel method for textile testing prioritizes human and animal welfare by utilizing an artificial blood-feeding system, replacing real animals and volunteers. The attractive blood-feeding device (ABFD), designed with the Hemotek® membrane feeding system, evaluated repellency of DEET, picaridin, and permethrin against *Aedes albopictus* (figure 12). Under choice conditions, 1% DEET and 2% picaridin showed significant repellency (>95% inhibition), while 2% permethrin exhibited none. Both 2% DEET and 2% picaridin demonstrated notable blood-feeding inhibition (>95%). In no-choice tests, 1% DEET and 2% picaridin exhibited strong repellency, with limited effects from 2% permethrin. Furthermore, permethrin (2%), picaridin (4%), and DEET (2%) displayed substantial blood-feeding inhibition. The ABFD's accuracy and reproducibility suggest wide application potential for basic mosquito physiology studies, novel repellent compound development, and product testing such as anti-mosquito fabrics. Future improvements in membrane and feeding unit systems promise enhanced assessment of insect repellents and blood-feeding inhibitors like pyrethroids [106].

6.10. A behavior assay system

The effectiveness of methods for controlling vectors, such as spatial repellents (SR), has been evaluated through a mosquito behaviour assay system. When conducting entomological studies, for the purpose of estimating the short-term concentrations of spatial repellent active ingredients (AI) in air spaces, the analytical techniques currently in use are not optimal. This study's objective was to build on earlier discoveries in order to verify a novel method of air sampling for the detection and measurement of concentrations of SR in the air in both laboratory and field environments. Dichlorodiphenyltrichloroethane (DDT) concentration in air samples was evaluated by a thermal desorption gas chromatography-mass spectrometry (TD GC-MS) technique. One-litre

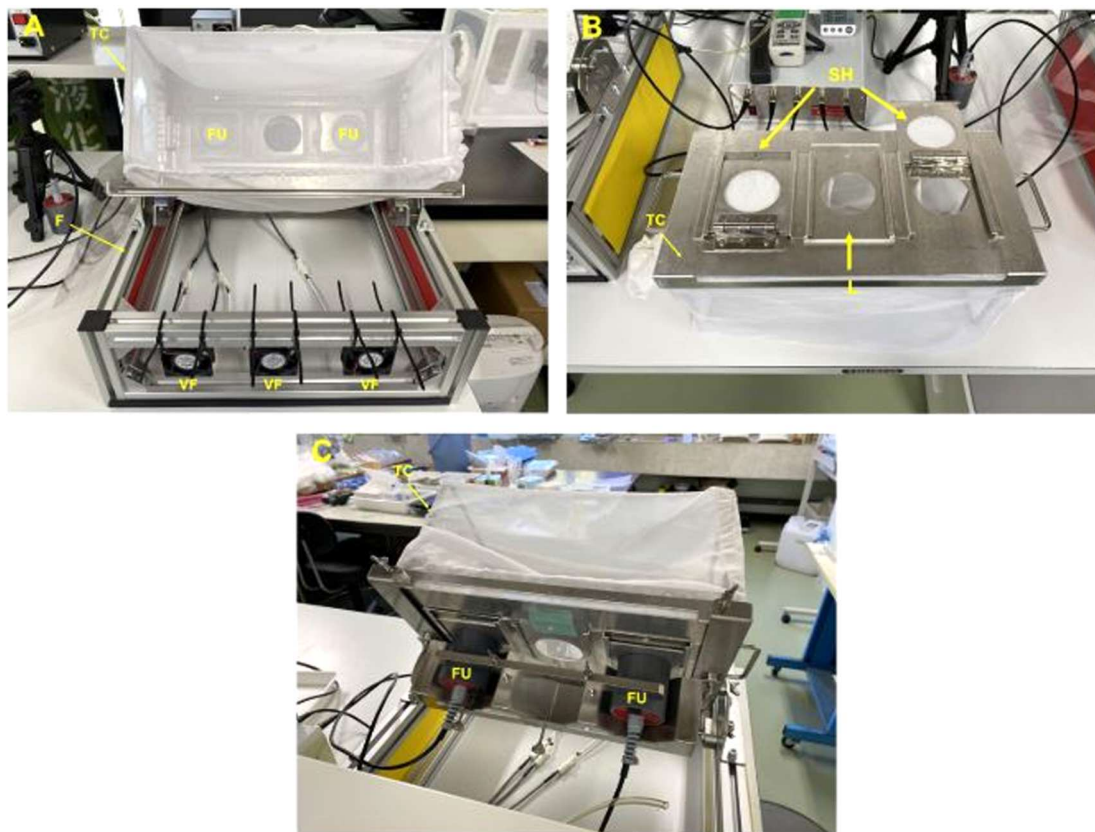


Figure 12. The ABFD test cage. (A) test cage fixed into the frame. (B) Test cage's bottom; One aperture (in the center) is sealed with a lid, while the other two are covered with sample holders made of binding cotton material. (C) Test cage's rear perspective. Through holes in the sample holder, feeding units are fastened to the cotton fabric behind the test cage. SH sample holder with L lid. Reproduced from [106]. CC BY 4.0.

air samples were collected every ten minutes from a three-chamber mosquito behaviour assay device during laboratory tests. The chamber with DDT-treated textiles showed significantly higher levels of airborne DDT compared to chambers without AI. In a field study, 57 air samples were collected from experimental huts without and with DDT. The samples from treated huts contained airborne DDT. The results of laboratory tests confirmed that the three-chamber system had significantly different DDT exposure conditions, establishing a chemical gradient that could be utilized to evaluate mosquito repellency [107].

6.11. Field test

Field tests evaluated the effectiveness of Cin-LNC-treated cloth against *Aedes* (during the day) and *Culex/Anopheles* (during the night) mosquitoes in rubber plantations in Perak, Malaysia. While rabbits with untreated nets stayed safe but attracted insects, those in cages without nets often suffered bites. Nets sprayed with Cin-LNC showed 100% repellency, shielding rabbits from mosquitoes throughout the day and keeping them away at night. In a similar vein, the repellency of coated and untreated bed nets was compared in Thailand, with the percentage of repellency determined by mosquito landings [39, 82].

7. Test methods to determine durability

To evaluate the resistance of the repellency, different tests were done following different methods, i.e., ISO II Test Method, ISO 105-C10 for color fastness to wash, ISO 105-B02 (Xenon arc) for color fastness to light, method 116-2005 for rubbing fastness [65].

8. Factors of fabric construction

For the construction of fabrics where mosquito repellency were imparted on fabrics of 79.92-150 [16] GSM were used by the researchers where EPI and PPI were maintained as 27×29 (79.92 GSM) [1, 67], 96×72 (131.25 GSM) [2, 79, 93], 80×64 (81.3 GSM) [92] etc (table 16).

Table 16. Factors considered for fabric construction and different standards to measure mosquito repellency.

Fabric construction	Standard to measure the resistance of repellency	References
Cotton woven fabric (GSM 131.25, EPI = 96, PPI = 72)	ISO 105- C06 (Wash fastness); ISO105-X12:2001(Rubbing fastness); ISO 105 BO2 (Light Fastness); AATCC61-A(Laundrying)	[79]
Polyester fabric (GSM = 79.92, EPI = 27, PPI = 29)		[1, 67]
Cotton (GSM = 131.25, EPI = 96, PPI = 72,) Scoured and bleached fabric.	AATCC test method 8–2007 (Rubbing fastness); ISO: 105-A02-1995 (Wash fastness); AATCC 16–2004 or ISO 105-B02 -Xenon arc (Light fastness); AATCC-61A (Laundrying)	[2, 33, 36, 37, 93]
100% acrylic RFD fabric (GSM = 150, EPI = 44, PPI = 37)	ISO 105-X12 (Rubbing fastness); ISO 105-C06 (Wash fastness); ISO 105 BO2 (Light fastness); AATCC-61A (Laundrying)	[16]
Nylon-6 RFD fabric (EPI=80, PPI=64, GSM 81.3)	ISO 105 BO2 (Light fastness); ISO 105-C06 (Wash fastness); ISO 105-X12 (Rubbing fastness); AATCC-61A (Laundrying); ISO 105 E04 (Perspiration);	[2, 65, 92]

Table 17. Fabric construction and impregnation method of LLIN.

Fabric construction	Type of textiles	Method of impregnation	References
Specific weight of 210 GSM with 170 mesh cm^{-2}	Cotton fabric	Polymer Coating	[108]
1.7 × 2.4 m blanket	Blankets (Manmade Fiber)	Binder	[109]
Blue shade cloth rolls, measuring 2.3 × 100 m, consist of 50% high-density polyethylene (HDPE) and weigh 80 GSM	Wall lining (Manmade Fiber)	Polymer Coating	[110]
150 denier HDPE monofilaments of the nets and six holes per net, where each hole was 4 × 4 cm^2	Polyethylene monofilament	Polymer Incorporation	[111]
Family size polyester mosquito nets range from 50 to 83 mg AI/m ² , depending on size, with a standard of 62 mg AI/m ² .	Polyethylene, Cotton, nylon, and undyed and dyed polyester	Slow-release capsule suspension (CS) Impregnation	[112]
Polyethylene and polyester fiber (≥ 12 holes cm^2 to ≥ 77 holes cm^2)	Window curtains (Manmade Fiber)	Glue Adhesion	[113]
120 × 30 cm net sample	Polyester nets	Binder	[61]
Rectangular single polyester fiber (120 × 150 × 180 cm) PermaNet [®] 2.0 bed nets	Bed nets	Tablet	[114]
Rectangular in shape (180 cm × 160 cm × 180 cm in length × width × height respectively) and dyed blue during manufacture	Net Fabric	Chemical Impregnation	[115]
Interceptor [®] & PermaNet [®] 2.0, a polyester based netting, Olyset [®] & NetProtect [®] polyethylene-based netting	Polyester and polyethylene	Chemical Impregnation	[116]

9. Mosquito repellent textiles

Mosquito repellency can be imparted on different types of textiles, i.e., long-lasting insecticide-treated net (LLIN), uniform blanket, etc Details on their construction, methods of impregnation, and major outcomes have been discussed briefly in tables 17 and 18 respectively.

9.1. Long-lasting insecticide-treated nets (LLIN)

Bed nets are widely endorsed by the WHO to combat disease-carrying mosquitoes. For smaller vectors like sandflies, additional treatment with synthetic insecticides (ITNs) is effective. Many malaria-prone countries implement universal LLIN coverage policies to reduce transmission. Various impregnation techniques globally enhance LLIN quality. Well-maintained LLINs can last three years with proper washing, gentle handling, and repairs. They include Bed Nets, Curtains, and Blankets, with types like Permanet 2.0, Care Plus net, and Net-protect among others [7, 108, 109].

9.1.1. Blanket

Kitau *et al* employed 1.7 × 2.4 m blankets impregnated with permethrin at 1130 mg m^{-2} using two binders, comparing treated and untreated versions. They treated each blanket individually with 4.16 ml of 50% Permethrin EC mixed in 1130 ml of water, aiming for a dosage of 0.5 g m^{-2} . This was done in a way that ensured the blanket was saturated without dripping. The blankets were thoroughly kneaded to achieve saturation. Each

Table 18. Nature of repellency and major outcome.

Nature of repellency	Outcome	References
Polymer-coating	To attach synthetic pyrethroids to bed net cloth, track LLINs' lingering bioactivity, and assess their laundry resistance	[108]
Chemical	Death rates in experimental huts for treated blankets (LLIB and ITB) were low. Olyset LLIN control only killed 31%, similar to unwashed LLIB.	[109]
Adhesive	It was determined which fixing products were most suited for attaching polyethylene DL walls. A comprehensive and flexible technique for installing DL households was created for regular implementation in regions where malaria is endemic.	[110]
Chemical	Up to 25 washes, MAGNet LN maintained its bioefficacy. The trial's observations regarding the effectiveness of MAGNet LN meet the WHOPES criteria for phase II evaluation.	[111]
Chemical	Enhance the insecticide's washability. Find out whether substrates treated with insecticides could survive 15–20 washings and perhaps meet WHO recommendations.	[112]
Spatial	Was helpful in measuring the impact of insecticide-treated mosquito netting. makes sure that no mosquito can settle inside the bioassay construct without coming into contact with the textile or tested netting.	[113]
Chemical	Provides satisfactory mortality (>80%) in bioassays with an exposure of 3 min following twenty standard washes.	[61]
Chemical	Produced more efficiency. Retained their insecticidal efficacy throughout twenty-one washings.	[114]
Chemical	Assumes certain things regarding the relationship between artificial washing carried out in a lab and durability over time. Phase I and II testing's twenty washes are meant to serve as a stand-in for pesticide durability.	[115]
Physical Barrier	Before washing started, no mosquito was able to eat through any of the four types of netting.	[116]

dipped blanket was stored at room temperature after being horizontally dried on plastic sheets in the shade until completely dry. So, Blanket is used as a mosquito repellent textile [109].

9.1.2. Durable wall lining (DL) material

Long-lasting wall lining, such as ZeroVector® DL, might be an additional or substitute vector control technique to the ones that are already in use. High-density polyethylene (HDPE) is the material used in the present DL that has been coated with deltamethrin. When applied to inside house walls, it serves as a persistent insecticidal reservoir. A few of the known drawbacks of traditional LLINs and IRS are addressed by DL. Household protection, in contrast to LLINs, is passive once installed and does not need nightly behavioral compliance. It also won't be affected by householder or donor tiredness brought on by yearly rounds of spraying. The installation process arguably holds the utmost significance in ensuring long-term durability in field settings and fostering initial household acceptance [110].

9.1.3. Eave sealants

Eave Sealants is a type of tents that is used as mosquito repellent textiles. Njoroge, M.M., *et al* described push–pull system where analyze new ideas and reevaluate tried-and-true enticing 'pull' and repulsive 'push' elements to influence how malaria vectors orient their odour in the peri-domestic area. These had translucent polycarbonate roofs and walls screened with fiberglass netting with a similar mesh size as the larger systems. Eave Sealants is made by this process [34].

9.1.4. Army uniform

One strategy to prevent mosquito bites and other arthropod vectors that spread a variety of horrible diseases is personal protection. Many nations, both military and civilian, use synthetic pyrethroid permethrin applied to fabric to repel arthropod vectors. Sukumaran, D., *et al* used the army uniform cloth (CVC 65-35) and the control sample consisted of identically sized sleeves made from army uniform fabric that were similarly sewn and simply had a binder treatment [71, 117].

10. Environmental hazards of mosquito-repellent textiles

Mosquito-repellent textiles have emerged as an innovative strategy for reducing the spread of vector-borne diseases such as malaria, dengue, and chikungunya. While these fabrics hold significant promise for public health, their environmental sustainability remains a pressing concern. The integration of repellents—whether DEET, synthetic pyrethroids such as permethrin, essential oils like citronella and neem, or microencapsulated formulations—introduces potential risks when such textiles are manufactured, used, cleaned, and ultimately

discarded. This section explores the major environmental hazards associated with mosquito-repellent textiles, with particular attention to the impact of laundering and post-consumer waste.

Mosquito-repellent compounds pose significant environmental hazards. These include contamination of water bodies with persistent pesticides that can affect aquatic organisms, disrupt ecosystems, and potentially lead to bioaccumulation and biomagnification in the food chain. Specifically, organophosphates and organochlorines used as mosquito repellents can be toxic to non-target aquatic species and may cause long-term environmental pollution. The presence of these pesticides in surface and groundwater sources can compromise water quality and harm biodiversity, emphasizing the need for careful management and the development of environmentally friendly alternatives [118]. Mosquito-repellent pesticides, like other chemical pesticides, pose environmental hazards through their mobility, persistence, and potential to disturb ecological and human health systems. Effective management strategies, such as using buffer zones and selecting fewer volatile formulations, are recommended to mitigate these risks [119]. Mosquito-repellent pesticides, like other pesticides, may persist in the environment and spread beyond the targeted area via drift, runoff, or leaching, contaminating soil, water sources, and air. These pesticides can adversely affect non-target species such as earthworms, which are vital for soil health, and natural predators or parasitoids that help control pest populations. The destruction of these organisms can lead to ecological imbalances and reduced biodiversity [120].

11. Challenges and future scopes

Scaling up the extraction process for essential oils and soaking larger quantities of fabrics presents a significant challenge in textile production. While smaller fabric pieces can be conveniently handled, the industrial application remains limited. The potential for achieving yellow-shaded multifunctional finished cotton textiles is promising; however, the issue of washing durability has not been adequately addressed [121]. Previous studies have shown a concerning lack of laundering stability for textiles treated with gelatine-Arabic gum microcapsules, raising questions about the longevity of treated fabrics under typical usage conditions. Furthermore, the application of microcapsules has been found to slightly affect the air permeability and absorbance properties of treated fabrics, posing additional challenges in maintaining desired textile characteristics. These alterations may impact the overall comfort and performance of the fabric, necessitating careful consideration in the development and application of treatment methods [57, 101]. Increasing the output of essential oil microcapsules, achieving a regulated and prolonged release of essential oils from microcapsules, and enhancing their stability and immobilization effectiveness on textile substrates continue to be challenges in the field today. Beyond technical challenges in fabric treatment, the broader issue of malaria control presents a significant obstacle. Despite the widespread use of Long-Lasting Insecticidal Nets (LLINs) as a vital tool in malaria prevention, there remains a concerning prevalence of malaria cases and related fatalities. This persistence can be attributed, at least in part, to underuse and a lack of awareness regarding basic maintenance methods for LLINs. Addressing these challenges requires a multifaceted approach, encompassing both technical innovations in fabric treatment processes and comprehensive education and outreach efforts to promote proper LLIN maintenance and utilization [7]. Only through concerted efforts to overcome these obstacles can we realize the full potential of fabric treatments for malaria control and textile enhancement. With the right application methods, textile substrates can be grafted with oil-containing microcapsules. Due to their fragile morphologies, microcapsules are still difficult to use effectively in standard industrial procedures. Also, it's necessary to establish specific regulatory standards for natural repellents to ensure quality and optimal application [36].

The potential of geraniol oil in creating mosquito repellent textiles for clothing presents a promising avenue for research [95]. The papers advocate for a thorough exploration into optimizing geraniol oil application on fabrics, focusing on enhancing durability and investigating alternative materials for improved performance. Priority should be given to methods enhancing the longevity of geraniol oil-treated fabrics, considering the low laundering stability observed with gelatin-Arabic gum microcapsules [112]. Research should delve into alternative encapsulation techniques or surface treatments to maintain repellent efficacy after multiple wash cycles. Exploring novel encapsulation materials or fabric treatments may broaden the applicability of mosquito repellent textiles [36]. While challenges persist regarding washing durability, potential niche applications such as disposable cloths or repellency bands warrant evaluation, especially for individuals in forested or urban risk zones. Developing effective methods for fabric retreatment is crucial for sustaining repellent efficacy. Investigating innovative post-wash replenishment approaches can enhance the practicality and usability of repellent-treated clothing [28]. Furthermore, integrating repellent textiles with existing mosquito control methods, particularly with untreated nets prevalent in retail markets, holds promise for enhancing mosquito control efforts in diverse settings [100]. More research can be done to see whether adding other advantageous chemicals to the essential oils will increase their bioactivity and bioavailability. Future research on the targeted administration of

microencapsulated oil on particular external stimuli has a great deal of potential. Additionally, it appears that creating tiny microcapsules will be a future area of study. Similarly, a less-explored field is offered by simultaneous grafting and coupled essential oil microencapsulation on textile substrates as well as the production of smaller capsules in the nano-range, which are suggested as promising avenues for further exploration [49, 57, 101].

12. Conclusion

The increasing global mosquito population poses a significant threat to human health due to disease transmission. The study categorizes research into application methods, assessment criteria, and material exploration. It provides a comprehensive analysis of both natural and synthetic repellents on diverse textile substrates. Synthetic repellents such as DEET and permethrin remain effective but raise concerns about toxicity, skin compatibility, and resistance, whereas natural repellents like essential oils and plant extracts offer safer and more sustainable alternatives, albeit with reduced durability. Advances in application techniques—particularly micro- and nanoencapsulation—have improved controlled release, wash resistance, and multifunctionality, enabling fabrics that combine repellency with antibacterial, antioxidant, and UV-protective properties.

However, although having some promising advancements in this particular field, various critical challenges remain. Some of these are to achieve a long-lasting effect after repeated washing, skin irritation, foul smell, or ecological effects, for the most effective synthetic ones. In addition to this, the cost-effectiveness and large-scale production of the environmentally benign options are yet to be checked. Future approaches should be focused on solving these gaps and developing standardized protocols, using non-toxic carriers, and also using smart delivery system. Combining synthetic and natural agents for their synergistic effects, and tailoring textiles for specific contexts such as military uniforms, healthcare, and household applications. Collaboration between textile engineers, chemists, entomologists, and public health authorities will be crucial in moving from laboratory innovation to commercially viable solutions. If the current limitations are overcome and thoroughly studied, mosquito-repellent textiles can be an economically feasible and sustainable intervention to barrier against vector-borne diseases, supporting global public health.

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Conflicts of interest

The authors have no relevant conflicts interests to disclose.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

- [1] Singh A and Sheikh J 2022 Synthesis of novel, coumarin-based, mosquito repellent-cum-multifunctional azo disperse dye for functional dyeing of polyester *J. Text. Inst.* **114** 1108–18
- [2] Singh A and Sheikh J 2023 Synthesis of a novel acid dye to impart mosquito repellency and UV protection to nylon *Progress in Color, Colorants and Coatings* **16** 207–19
- [3] Ap dos Santos D, Oliveira A M, Cerize N N P, Manhani K C, Santos D S, de Araujo H C, Costa S A and Costa S M 2022 Synthesis of polymeric particles with insect repellent for potential application on textile substrates *Mater. Chem. Phys.* **280** 125662
- [4] Pavan M, Rani A, Jhang T and Singh S P 2023 Developing herbal mosquito repellent cotton fabric using the optimized process variables for the safe environment *Mater. Today Proc.* **78** 900–6
- [5] Liu Y, Lillepold K, Semenza J C, Tozan Y, Quam M B M and Rocklöv J 2020 Reviewing estimates of the basic reproduction number for dengue, Zika and chikungunya across global climate zones *Environ. Res.* **182** 109114
- [6] Ho K-C, Mo S-Y, Tang B-B, Wong T-Y and Mo M 2019 Comparing mosquito repellency efficacy on textiles sprayed with DEET and Permethrin *Chemical & Pharmaceutical Research* **1** 1–4
- [7] N'Guessan G K D, Coulibaly F H, Barreaux A M G, Yapo R J, Adou K A, Tia E and Fournet F 2022 Qualitative study on the use and maintenance of long-lasting insecticidal nets (LLINs) in Bouake (Cote d'Ivoire), 17 months after the last mass distribution campaign *Malar. J.* **21** 228
- [8] WHO 2024 *World Health Organization (WHO)* <https://who.int/news-room/fact-sheets/detail/malaria>
- [9] Matthews B J 2019 *Aedes aegypti*. *Trends in Genetics* **35** 470–1
- [10] WHO 2023 Dengue - global situation <https://who.int/emergencies/disease-outbreak-news/item/2023-DON498>
- [11] Katz T M, Miller J H and Hebert A A 2008 Insect repellents: historical perspectives and new developments *Journal of the American Academy of Dermatology* **58** 865–71
- [12] Hazarika H, Krishnatreyya H, Tyagi V, Islam J, Gogoi N, Goyari D, Chattopadhyay P and Zaman K 2022 The fabrication and assessment of mosquito repellent cream for outdoor protection *Sci. Rep.* **12** 2180
- [13] Mokhtari J, Shams-Nateri A and Ferdosi P 2014 Synthesis and characterization of novel reactive dyes with simultaneous insect-repellent and anti-bacterial properties *Fibers Polym.* **15** 1369–74
- [14] Singh N and Sheikh J 2021 Sustainable development of mosquito-repellent, flame-retardant, antibacterial, fragrant and antioxidant linen using microcapsules containing *Thymus vulgaris* oil in *in situ* generated chitosan-phosphate *Cellulose* **28** 2599–614
- [15] Malengier B, Goessens T, Mafo F F, De Vrieze M, Van Langenhove L, Wanji S and Lynen F 2015 Model-based determination of the influence of textile fabric on bioassay analysis and the effectiveness of a textile slow-release system of DEET in mosquito control *Pest Manag Sci* **71** 1165–74
- [16] Singh A and Sheikh J 2023 Synthesis of a novel cationic dye to impart mosquito-repellent and UV protection to an acrylic fabric *ACS Omega* **8** 10214–24
- [17] Kumar A, Singh A and Sheikh J 2023 Boric acid crosslinked chitosan microcapsules loaded with frankincense oil for the development of mosquito-repellent, antibacterial, antioxidant, and flame-retardant cotton *Int. J. Biol. Macromol.* **248** 125874
- [18] Parvez A A, Hossain M J, Hossain M Z, Sohan M S H, Hoque F, Ahsan M H and Hoque M S 2023 Mosquito repellent fabric: Development and characterization of peppermint and garlic mixture finish on knitted fabric to examine mosquito repellency *Heliyon*. **9** e15944
- [19] Raja A, Kawlekar S, Saxena S, Arputharaj A and Patil P 2015 Mosquito protective textiles - a review *International Journal of Mosquito Research* **2** 49–53
- [20] Fulton A C, Thum M D, Jimenez J, Camarella G, Cilek J E and Lundin J G 2023 Long-term insect repellent electrospun microfibers from recycled poly(ethylene terephthalate) *ACS Appl. Mater. Interfaces* **15** 44722–30
- [21] Place L W, Gulcius-Lagoy S M and Lum J S 2017 Preparation and characterization of PHMB-based multifunctional microcapsules *Colloids Surf., A* **530** 76–84
- [22] Wyrębska Ł, Szuster L, Masłowska-Lipowicz I, Ławińska K and Jagiełło J 2020 Permethrin application on polyamide and polyamide-polypropylene knitted fabrics *Fibres and Textiles in Eastern Europe* **28** 72–5
- [23] Zhou C, Stevie F and Garcia R 2020 Analysis of permethrin treated fabric using ToF-SIMS. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing Measurement, and Phenomena* **38** 1–8

- [24] Apiwathnasorn C, Sungvornyothin S, Wang X and Wang L 2021 Development of mosquito repellent textile using zanthoxylum limonella essential oil with knife-coating process: a preliminary report *Southeast Asian Journal of Tropical Medicine and Public Health* **52** 517–26
- [25] Murtaza M, Hussain A I, Kamal G M, Nazir S, Chatha S A S, Asmari M, Uddin J and Murtaza S 2023 Potential applications of microencapsulated essential oil components in mosquito repellent textile finishes *Coatings* **13** 1467
- [26] Mohamed A L, El-Zawahry M, Hassabo A G and Abd El-Aziz E 2023 Encapsulated lemon oil and metal nanoparticles in biopolymer for multifunctional finishing of cotton and wool fabrics *Ind. Crops Prod.* **204** 117373
- [27] Kamari A, Yusoff S N M, Wong S T S, Phillip E, Hargreaves J S J and Othman H 2021 Betel essential oil-loaded lipid-core nanocapsules as mosquito repellent spray formulations for fabric finishes *J. Text. Inst.* **114** 10–21
- [28] Ciera L, Beladjal L, Van Landuyt L, Menger D, Holdinga M, Mertens J, Van Langenhove L, De Clerk K and Gheysens T 2019 Electrospinning repellents in polyvinyl alcohol-nanofibres for obtaining mosquito-repelling fabrics *R. Soc. Open Sci.* **6** 182139
- [29] Muñoz V, Buffa F, Molinari F, Hermida L G, García J J and Abraham G A 2019 Electrospun ethylcellulose-based nanofibrous mats with insect-repellent activity *Mater. Lett.* **253** 289–92
- [30] Romi R, Lo Nostro P, Bocci E, Ridi F and Baglioni P 2005 Bioengineering of a cellulosic fabric for insecticide delivery via grafted cyclodextrin *Biotechnol Prog.* **21** 1724–30
- [31] Singh A and Sheikh J 2022 Development of mosquito repellent, antibacterial, antioxidant and UV protective cotton using a novel method of azoic dyeing with terminalia chebula *J. Nat. Fibers* **19** 9642–55
- [32] Wen W, Zhang Q, Jiang Y, Zhao R, Chen J, Shi Y and Tan L 2024 Green modifications for rendering cotton fabric with antibacterial, anti-mite, and mosquito-repellent functions using single natural eugenol *Chem. Eng. J.* **492** 152194
- [33] Kantheti P, Gupta A K and Rajitha I 2023 Sustainable mosquito repellent finish on cotton using Eucalyptus globulus leaf dye extracts *Indian Journal of Fibre & Textile Research* **48** 346–52
- [34] Njoroge M M, Fillinger U, Saddler A, Moore S, Takken W, van Loon J J A and Hiscox A 2021 Evaluating putative repellent ‘push’ and attractive ‘pull’ components for manipulating the odour orientation of host-seeking malaria vectors in the peri-domestic space *Parasit Vectors* **14** 42
- [35] Masha J F et al 2022 Effectiveness and cost-effectiveness against malaria of three types of dual-active-ingredient long-lasting insecticidal nets (LLINs) compared with pyrethroid-only LLINs in Tanzania: a four-arm, cluster-randomised trial *Lancet* **399** 1227–41
- [36] Endris J and Govindan N 2021 Dyeing and finishing of cotton fabric with eucalyptus leaves extracts *Res. J. Text. Apparel* **25** 193–208
- [37] Teli M D and Chavan P P 2017 Dyeing of cotton fabric for improved mosquito repellency *J. Text. Inst.* **109** 427–34
- [38] Sarişik M, Kartal G E, Erkan G and Etkeser S 2021 Alternative methods for transferring mosquito repellent capsules containing bio-based citronella oil to upholstery fabrics: coating and printing *J. Coat. Technol. Res.* **19** 323–36
- [39] Kamari A, Yusoff S N M, Wong S T S, Yusof N, Othman H, Hussein M Z and Phillip E 2022 Development of anti-mosquito spray formulation based on lipid-core nanocapsules loaded with cinnamaldehyde for fabrics application *Fibers Polym.* **23** 2156–66
- [40] Bramhecha I and Sheikh J 2024 Inherent mosquito repellent-cum-multifunctional polyurethane for multifunctional coating of cotton fabric *J. Ind. Eng. Chem.* **132** 247–58
- [41] Periyasamy A P, Venkataraman M, Kremenakova D, Militky J and Zhou Y 2020 Progress in sol-gel technology for the coatings of fabrics *Materials (Basel)* **13**
- [42] Ramya K and Maheshwari V 2014 Development of eco friendly mosquito repellent fabric finished with andrographis paniculata plant extracts *International Journal of Pharmacy and Pharmaceutical Sciences* **6** 115–7
- [43] Luan K et al 2021 Mosquito-textile physics: a mathematical roadmap to insecticide-free, bite-proof clothing for everyday life *Insects* **12** 636
- [44] Rashkov P 2021 A model for a vector-borne disease with control based on mosquito repellents: A viability analysis *J. Math. Anal. Appl.* **498** 124958
- [45] Gungordu Er S, Bulathsinghala R, Kizilates S B, Li B, Ryan R, Tabish T A, Dharmasena I and Edirisinghe M 2025 Multifunctional conductive nanofibers for self-powered glucose biosensors *Adv. Sci.* **12** 2416320
- [46] Dai Y, Sun D, O'Rourke D, Velusamy S, Sundaram S and Edirisinghe M 2025 Harnessing cow manure waste for nanocellulose extraction and sustainable small-structure manufacturing *J. Clean. Prod.* **509** 145530
- [47] Aydogdu M O, Delbusso A and Edirisinghe M 2025 A battery powered approach to pressurised spinning: Introducing the sustainability concept and shaping the future of fibre production methodologies *Appl. Energy* **397** 126331
- [48] Ghayempour S and Montazer M 2016 Micro/nanoencapsulation of essential oils and fragrances: Focus on perfumed, antimicrobial, mosquito-repellent and medical textiles *J. Microencapsul* **33** 497–510
- [49] Tariq H, Rehman A, Raza Z A, Kishwar F and Abid S 2023 Recent progress in the microencapsulation of essential oils for sustainable functional textiles *Polym. Bull.* **81** 7585–629
- [50] Anuar A A and Yusof N 2016 Methods of imparting mosquito repellent agents and the assessing mosquito repellency on textile *Fashion and Textiles* **3** 12
- [51] Elsayed G A and Hassabo A G 2021 Insect repellent of cellulosic fabrics (a review) *Letters in Applied NanoBioScience* **11** 3181–90
- [52] Shirish Kumar G V N, Maheshwari R and Prabhu K H 2007 Recent developments of mosquito repellent textiles *ATA Journal.* **18** 38–9
- [53] Shivankar V S, Shinde I, Mulla A and Raichurkar P P 2019 Eco-friendly mosquito repellent textiles *Colourage.* **66** 1–2
- [54] Saraf N M and Alat D V 2005 Esoteric and aesthetic finishes on textiles *International Dyer* **190** 24–7
- [55] Nair S U 2004 Textile evaluation using biotechnological approach: an overview in Indian textile industry *BTRA Scan.* **34** 16–19
- [56] Menezes E and Choudhari M 2007 Special finishes and effects *AATCC Review.* **7** 29–32
- [57] Specos M M, Garcia J J, Tormesello J, Marino P, Vecchia M D, Tesoriero M V and Hermida L G 2010 Microencapsulated citronella oil for mosquito repellent finishing of cotton textiles *Trans R Soc Trop Med Hyg.* **104** 653–8
- [58] Fei B and Xin J H N 2007 N-diethyl-m-toluamide-containing microcapsules for bio-cloth finishing *Am J Trop Med Hyg.* **77** 52–7
- [59] N'Guessan R, Knols B G, Pennetier C and Rowland M 2008 DEET microencapsulation: a slow-release formulation enhancing the residual efficacy of bed nets against malaria vectors *Trans R Soc Trop Med Hyg.* **102** 259–62
- [60] Revay E E, Junnila A, Xue R D, Kline D L, Bernier U R, Kravchenko V D, Qualls W A, Ghattas N and Muller G C 2013 Evaluation of commercial products for personal protection against mosquitoes *Acta Trop.* **125** 226–30
- [61] Yates A, N'Guessan R, Kaur H, Akogbeto M and Rowland M 2005 Evaluation of KO-Tab 1-2-3: a wash-resistant ‘dip-it-yourself’ insecticide formulation for long-lasting treatment of mosquito nets *Malar. J.* **4** 52
- [62] Türkoğlu G C, Sarıışık A M, Erkan G, Yıkılmaz M S and Kontart O 2020 Micro- and nano-encapsulation of limonene and permethrin for mosquito repellent finishing of cotton textiles *Iran. Polym. J.* **29** 321–9

- [63] Duchon S, Bonnet J, Marcombe S, Zaim M and Corbel V 2009 Pyrethrum: a mixture of natural pyrethrins has potential for malaria vector control *J. Med. Entomol.* **46** 516–22
- [64] Agramonte N M, Bloomquist J R and Bernier U R 2017 Pyrethroid resistance alters the blood-feeding behavior in Puerto Rican *Aedes aegypti* mosquitoes exposed to treated fabric *PLoS Negl. Trop. Dis.* **11** e0005954
- [65] Teli M D and Chavan P P 2016 Synthesis of reactive dye to impart mosquito repellency to nylon *The Journal of The Textile Institute.* **108** 1–9
- [66] Teli M D and Chavan P P 2016 Modified application process on cotton fabric for improved mosquito repellency *The Journal of The Textile Institute.* **108** 915–21
- [67] Singh A and Sheikh J 2021 Development of multifunctional polyester using disperse dyes based through a combination of mosquito repellents *J. Mol. Struct.* **1232**
- [68] Singh A and Sheikh J 2022 Development of mosquito-repellent and antibacterial nylon *Indian J. Fibre Text. Res.* **47** 468–70
- [69] Sibanda M, Focke W, Braack L, Leuteritz A, Brunig H, Tran N H A, Wieczorek F and Trumper W 2018 Bicomponent fibres for controlled release of volatile mosquito repellents *Mater. Sci. Eng. C: Mater. Biol. Appl.* **91** 754–61
- [70] Lei L Y, Mao Y H, Xu X F, Zheng J Q, Zheng Q K, Guan Y and Fan X M 2014 Effect of N,N-diethyl-m-toluamide on the structure and dyeing properties of meta-aramid and para-aramid fibre *Color. Technol.* **130** 349–56
- [71] Sukumaran D, Sharma A K, Wasu Y H, Pandey P and Tyagi V 2014 Knockdown and repellent effect of permethrin-impregnated army uniform cloth against *Aedes aegypti* after different cycles of washings *Parasitol Res.* **113** 1739–47
- [72] Hebeish A, El-Sawy S M, Ragaie M, Hamdy I A, El-Bisi M K and Abdel-Mohdy F A 2014 New textiles of biocidal activity by introduce insecticide in cotton-poly (GMA) copolymer containing beta-Cd *Carbohydr Polym.* **99** 208–17
- [73] Abdel-Mohdy F A, Gaballa Fouda M M, Rehan M F and Ali A S 2009 Repellency of controlled-release treated-cotton fabrics based on permethrin and bioallethrin against mosquitoes *J. Textile Inst.* **100** 695–701
- [74] DeRaedt Banks S, Orsborne J, Gezan S A, Kaur H, Wilder-Smith A, Lindsey S W and Logan J G 2015 Permethrin-treated clothing as protection against the dengue vector, *aedes aegypti*: extent and duration of protection *PLoS Negl. Trop. Dis.* **9** e0004109
- [75] Richards S L, Agada N, Balanay J A G and White A V 2018 Permethrin treated clothing to protect outdoor workers: evaluation of different methods for mosquito exposure against populations with differing resistance status *Pathog Glob Health.* **112** 13–21
- [76] Hebeish A, Hamdy I A, El-Sawy S M and Abdel-Mohdy F A 2010 Preparation of durable insect repellent cotton fabric through treatment with a finishing formulation containing cypermethrin *J. Textile Inst.* **101** 627–34
- [77] Martin N J, Nam V S, Lover A A, Phong T V, Tu T C and Mendenhall I H 2020 The impact of transfluthrin on the spatial repellency of the primary malaria mosquito vectors in Vietnam: anopheles dirus and anopheles minimus *Malar. J.* **19** 9
- [78] Bernier U R, Gurman P, Clark G G and Elman N 2015 Functional micro-dispensers based on micro-electro-mechanical-systems (MEMS) integrated with fabrics as functional materials to protect humans from mosquito feeding *J. Control. Release* **220** 1–4
- [79] Singh A and Sheikh J 2021 Development of mosquito repellent, antibacterial, antioxidant and UV protective cotton using a novel method of azoic dyeing with terminalia chebula *J. Nat. Fibers* **19** 642–55
- [80] Anwar F, Abbas M, Malik M H, Cheema A A, Tariq S, Afzal W and Khan A 2023 Development of mosquito-repellent camouflage fabric using eucalyptus oil with moringa oleifera gum *ChemEngineering* **7** 64
- [81] Bhatt L and Kale R D 2019 Lemongrass (*Cymbopogon Flexuosus* Steud.) wats treated textile: a control measure against vector-borne diseases *Heliyon* **5** e02842
- [82] Subjalearndee N, Phanomkate N and Intasanta V 2017 A novel and practical process to sustainable mosquito-borne disease prevention *Fibers Polym.* **18** 2235–47
- [83] Singh N and Sheikh J 2021 Multifunctional linen fabric obtained through finishing with chitosan-gelatin microcapsules loaded with cinnamon oil *J. Nat. Fibers* **19** 4780–90
- [84] P V, B S, Km P and R K 2017 Microencapsulated lemongrass oil for mosquito repellent finishing of knitted cotton wear *Asian Journal of Pharmaceutical and Clinical Research* **10** 303–7
- [85] Soroh A, Owen L, Rahim N, Masania J, Abioye A, Qutachi O, Goodyer L, Shen J and Laird K 2021 Microemulsification of essential oils for the development of antimicrobial and mosquito repellent functional coatings for textiles *J. Appl. Microbiol.* **131** 2808–20
- [86] Mahmud M H, Raihan M T, Shakhik M T, Khan F T and Islam M T 2023 Dragon fruit (*hylocereus polyrhizus*): a green colorant for cotton fabric *Colorants [Internet]* **2** 230–44
- [87] Mamun M A, Haji A, Mahmud M H, Repon M R and Islam M T 2023 Bibliometric evidence on the trend and future direction of the research on textile coloration with natural sources *Coatings* **13** 413
- [88] Islam M T, Farhan M S and Mahmud M H 2024 Green extraction of dyes and pigments from natural resources *Renewable Dyes and Pigments* editor, ed S U I Islam (Elsevier) **19**–36
- [89] Priya R, Das S, Sanjana N and Shivani B 2021 Finishing of textiles with the extract of senna auriculata (*Cassia auriculata*) *Man-Made Text. India* **49** 153–7
- [90] Gopalakrishnan D 2007 Mosquito repellent fabrics *Man-Made Text. India* **50** 15–8
- [91] Vijayalakshmi D and Vigneswaran C 2010 Cotton mosquito repellent fabrics and their performance *Melliand International* **16** 46–7
- [92] Singh A and Sheikh J 2022 Synthesis and application of a novel cold brand reactive dye to impart colouration, mosquito repellency, and UV protection to nylon *Arabian J. Chem.* **15** 104339
- [93] Singh A and Sheikh J 2022 Preparation of mosquito repellent, antibacterial and UV protective cotton using a novel, chitosan-based polymeric dye *Carbohydr Polym* **290** 119466
- [94] Miro Specos M M, Garcia J J, Gutierrez A C and Hermida L G 2016 Application of microencapsulated biopesticides to improve repellent finishing of cotton fabrics *J. Text. Inst.* **108** 1454–60
- [95] Anuar S N S, Affandi N D N, Safian M F and Yusof N 2022 Morphological characterization of microencapsulated geraniol oil *Malaysian Journal of Microscopy* **18** 153–63
- [96] Qosim N, Majd H, Huo S, Edirisinghe M and Williams G R 2024 Hydrophilic and hydrophobic drug release from core (polyvinylpyrrolidone)-sheath (ethyl cellulose) pressure-spun fibers *Int. J. Pharm.* **654** 123972
- [97] Majd H, Gultekinoglu M, Bayram C, Karaosmanoğlu B, Taşkıran E Z, Kart D, Erol Ö D, Harker A and Edirisinghe M 2024 Biomedical efficacy of garlic-extract-loaded core-sheath plasters for natural antimicrobial wound care *Macromol. Mater. Eng.* **309** 2400014
- [98] Majd H, Gultekinoglu M, Bayram C, Karaosmanoğlu B, Taşkıran E Z, Kart D, Erol Ö D, Harker A and Edirisinghe M J M M 2024 Biomedical efficacy of garlic-extract-loaded core-sheath plasters for natural antimicrobial wound care *Macromol. Mater. Eng.* **309** 2400014
- [99] Majd H, Harker A, Edirisinghe M and Parhizkar M 2022 Optimised release of tetracycline hydrochloride from core-sheath fibres produced by pressurised gyration *J. Drug Delivery Sci. Technol.* **72** 103359

- [100] Bonet-Aracil M, Bou-Belda E, Gisbert-Payá J and Ibañez F 2019 *In situ* test: cotton sheets against mosquito bites in India *Cellulose* **26** 4655–63
- [101] Tariq Z, Izhar F, Malik M H, Oneeb M, Anwar F, Abbas M and Khan A 2022 Development of functional textile via microencapsulation of peppermint oils: a novel approach in textile finishing *Res. J. Text. Apparel* **28** 337–49
- [102] Teli M D and Chavan P 2016 Application of gelatine based microcapsules containing mosquito repellent oils on cellulosic biopolymer *Journal of Bionanoscience* **10** 390–5
- [103] Tariq Z, Izhar F, Gmd Z, Zulfiqar A, Malik M H, Oneeb M and Khan A 2022 Fabrication of highly durable functional textile through microencapsulation of organic citronella oil *Ind. Crops Prod.* **190** 115878
- [104] Luan K, McCord M G, West A J, Cave G, Travanty N V, Apperson C S and Roe R M 2023 Mosquito blood feeding prevention using an extra-low DC voltage charged cloth *Insects* **14** 405
- [105] Correa-Morales F et al 2019 Bioefficacy of two nonpyrethroid insecticides for targeted indoor residual spraying against pyrethroid-resistant aedes aegypti *J. Am. Mosq. Control Assoc.* **35** 291–4
- [106] Morimoto Y, Kawada H, Kuramoto K Y, Mitsuhashi T, Saitoh T and Minakawa N 2021 New mosquito repellency bioassay for evaluation of repellents and pyrethroids using an attractive blood-feeding device *Parasit Vectors* **14** 151
- [107] Martin N J, Smith P A, Achee N L and DeLong G T 2013 Determining airborne concentrations of spatial repellent chemicals in mosquito behavior assay systems *PLoS One* **8** e71884
- [108] Faulde M, Albiez G and Nehring O 2012 Novel long-lasting impregnation technique transferred from clothing to bednets: extended efficacy and residual activity of different pyrethroids against *Aedes aegypti* as shown by EN ISO 6330-standardized machine laundering *Parasitol Res* **110** 2341–50
- [109] Kitau J et al 2014 Laboratory and experimental hut evaluation of a long-lasting insecticide treated blanket for protection against mosquitoes *Parasit Vectors* **7** 129
- [110] Messenger L A, Larsen M L, Thomas J H and Rowland M 2014 Installation of insecticide-treated durable wall lining: evaluation of attachment materials and product durability under field conditions *Parasit Vectors* **7** 508
- [111] Kasinathan G, Sahu S S, Tharmalingam V, Swaminathan S, Rahi M and Purushothaman J 2019 Evaluation of MAGNet, a long-lasting insecticidal mosquito net against *Anopheles fluviatilis* in experimental huts in India *Malar. J.* **18** 59
- [112] Tunku P K, Sudi W S, Kaur H, Magesa S M and Rowland M 2021 Bio-efficacy and wash-fastness of a lambda-cyhalothrin long-lasting insecticide treatment kit (ICON(R)) Maxx against mosquitoes on various polymer materials *Malar. J.* **20** 387
- [113] Denham S, Eisen L, Beaty M, Beaty B J, WCt B and Saavedra-Rodriguez K 2015 Two novel bioassays to assess the effects of pyrethroid-treated netting on knockdown-susceptible versus resistant strains of aedes aegypti *J. Am. Mosq. Control Assoc.* **31** 52–62
- [114] Kayedi M H, Khamisabadi K, Haghdoost A A, Kayedi Z, Fallahi S and Abdali N 2017 Short and long term evaluation of the efficiency of PermaNet(R) 2.0 bed net against environmental factors and washing using bioassay tests *Rev Inst Med Trop Sao Paulo.* **59** e18
- [115] Martin J L et al 2022 Durability of three types of dual active ingredient long-lasting insecticidal net compared to a pyrethroid-only LLIN in Tanzania: methodology for a prospective cohort study nested in a cluster randomized controlled trial *Malar. J.* **21** 96
- [116] Atieli F K, Munga S O, Ofulla A V and Vulule J M 2010 The effect of repeated washing of long-lasting insecticide-treated nets (LLINs) on the feeding success and survival rates of *Anopheles gambiae* *Malar. J.* **9** 304
- [117] McCurry J 2007 Aspiring to the heights of textile innovation *International Dyer.* **192** 22–4
- [118] Garba Z N et al 2021 Risk assessment and the adsorptive removal of some pesticides from synthetic wastewater: a review *Beni-Suef Univ. J. Basic Appl. Sci.* **10** 19
- [119] Oaya C, Malgwi A, Degri M and Samaila A J A S 2019 Impact of synthetic pesticides utilization on humans and the environment: an overview *Agric. Sci. Technol.* **11** 279–86
- [120] Yadav I C and NLJEs D 2017 Pesticides Classification and its Impact on Environment *Environ. Sci. & Engg.* **6** 140–58
- [121] Vasugl N, Prabha R and Kanimozhi M 2010 Effect of mosquito-repellent finish on cotton fabric *Textile Magazine.* **51** 85–90