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Effect of tea tree oil on mosquito repellency characterization of cotton fabric

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Abstract
This study evaluated the efficacy of tea tree oil as a natural mosquito repellent finish on 100% cotton fabric. Using the pad-dry-cure procedure, the oil was directly applied to cotton fabric. In a laboratory environment, treated and untreated control samples were evaluated against *Aedes aegypti* and *Anopheles stephensi* using standardized exposure assays. The treated fabrics showed consistently high repellency, with percentages of repellency ranging from 94% to 100% during observation periods and total repellency measured at 24 hours. The knockdown results demonstrated acute effects that were species-dependent, with *Anopheles stephensi* showing more immediate incapacitation than *Aedes aegypti*. The findings indicate that the effective incorporation of tea tree oil into cotton fabric can greatly improve the fabric's ability to repel mosquitoes.

Keywords: Tea tree, cotton, application, direct, mosquitoes, repellency, knockdown

Introduction
Compared to metropolitan regions, rural areas have a higher mosquito density. Unsanitary environments, farming practices, cultural activities, and inadequate infrastructure all contribute to mosquito survival. Except for areas that are constantly covered in ice, they can be found all over the planet. Almost three-fourths of the approximately 3,500 mosquito species that have been identified are indigenous to the humid tropics and subtropics [1]. In most developing nations, including India, the prevalence of vector-borne diseases has emerged as a serious public health concern. Since mosquitoes are the source of numerous deadly diseases, they have been recognized as the most critical vector. As a result, mosquitoes may rank among the world's most deadly insects.

The parasite disease malaria is spread by Anopheline mosquitoes. It is thought to cause 249 million cases worldwide and kills over 600,000 people annually. Children under the age of five account for the majority of fatalities. The most common viral disease spread by Aedes mosquitoes is dengue. With an estimated 96 million symptomatic cases and 40,000 fatalities annually, dengue poses a threat to over 3.9 billion people in more than 132 countries. Chikungunya fever, Zika virus fever, yellow fever, West Nile fever, and Japanese encephalitis are other viral illnesses spread by vectors and are all spread by mosquitoes [2]. The National Vector Borne Disease Control Programme of India has documented several mosquito-borne diseases, primarily filariasis, chikungunya, Japanese encephalitis, dengue, and malaria [3].

Our ancestors had investigated a variety of plants in various regions, some of which had repellent or mosquito-cidal properties. To keep mosquitoes away, various plant parts, such as leaves, bark, roots, etc., were gathered and fumigated. In addition, traditional methods of mosquito defense were used throughout the nation, including fumigation, skin application of extracts, hanging plants or their parts, burning lamps with plant oil extracted, spraying plant extracts, etc. To functionalize the textile substrates, several novel finishing processes have been developed at present [4]. Among these, mosquito repellent finishes have gained significant attention. Mosquito repellent can be sprayed on skin, clothes, or other surfaces to stop mosquito bites. The naturally occurring repellent components are derived from herbs. Phytochemicals (secondary metabolites) found in herbs, such as tannins, phenols, citral, camphene, and others, aid in mosquito defense.

Plant essential oils exhibited stronger mosquito-repelling properties than plant extracts. Numerous plants contain essential oils, which are naturally occurring volatile compounds [5]. A well-known essential oil from Australia is tea tree oil, often known as melaleuca oil. The antibacterial, antimicrobial, and anti-inflammatory qualities of this oil are well documented. However, new research also indicates that tea tree oil might work well as an insect repellent. According to field tests, tea tree oil-based repellents work well against biting midges, bush flies, and mosquitoes [6].

Natural repellents made from plants have become increasingly popular because they are eco-friendly, non-toxic, and biodegradable. Essential oils derived from plants like cinnamon, eucalyptus, lemongrass, and citronella are frequently utilized for their repellent qualities [7]. These oils are volatile substances that produce a vapor barrier, which hinders mosquitoes from approaching the wearer.

Methodology

Application method: Tea tree oil was directly applied to the 100% cotton fabric using citric acid as the cross-linking agent to enhance binding and durability.

To develop mosquito repellent fabric by the direct method, the tea tree oil was applied directly to the cotton fabric using a padding bath. Citric acid employed as a cross-linking agent to enhance the fixation of the oils onto the fabric. The padding solution was prepared using oil ratio of 1.0 and optimized citric acid concentration. The treated fabric was then padded, dried, and cured under controlled conditions and the application process was optimized.

Optimization of concentration of citric acid: To optimize the concentration of citric acid, four different concentrations, 5, 6, 7 and 8 percent on weight of fabric (owf), were tested with the ratio of oil, while other variables were kept constant, such as the material to liquor ratio of 1:20 and the duration of treatment i.e., 30 minutes. Cotton fabric samples were immersed in the padding solution for 30 minutes at room temperature with periodic stirring, then passed through the padding mangle at a pneumatic pressure of 2 kg/cm^2. The fabric was then dried at 80-85 °C for five minutes and cured at 110 °C for three minutes. The concentration of citric acid that resulted in the lowest bending length and the highest crease recovery angle was selected as optimum.

Examination of treated fabric using Scanning Electron Microscopy (SEM)

Using a scanning electron microscope (SEM), the presence of treatment components in the final fabric samples was investigated. To examine surface morphological changes following treatment, both treated and untreated (control) samples were examined.

Evaluation of treated fabrics' mosquito repellency: The modified cage test and the cone test were used to determine how well the treated fabrics repelled mosquitoes.

Repellency behavioural test or cage test

Two controls samples hanging on opposing facets of an empty cage and two treated samples hanging on different facets of the same cage were used to assess the mosquitoes' resistance to treated fabrics in a lab setting during the day. The mosquitoes (specimens), which had been deprived of food and water for at least four hours before exposure, were observed from the upper facet of the cage. Fifty female *Anopheles stephensi* mosquitoes were released into the cage, and observations were made till twenty-four hours. The following formula was used to record and compute the number of mosquitoes on the treated and controls fabric samples:

$$\text{Mosquito Repellency (\%)} = \frac{\text{Number of specimen on controlled sample}}{\text{Total exposed specimen in the cage}} \times 100$$

Cone/toxicity test

Cone tests were used to measure the toxicity of mosquito-cidal or mosquito-repellent fabric and to find out how many insects died after being exposed to it. To verify the knockdown effect, 20 non-blood-fed mosquitoes between the ages of 2 and 5 days were used. To minimize disruption during testing, the test fabric sample was positioned underneath the cone, and the mosquitoes were injected in four batches, each containing five mosquitoes. The sample was exposed to each batch for about three minutes. After being extracted from the cones using a suction tube and aspirator, the mosquitoes were put in a glass cylinder with a sucrose solution inside a condition chamber, and after a day, observations were made. The percent of knockdown or repellency was determined using the following formula:

$$\text{Mosquito repellency or knockdown \%} = \frac{\text{Number of knockdowns}}{\text{Number of specimens used}} \times 100$$

Assessment of the various characteristics of treated fabric

The fabric samples were conditioned for 24 hours under conventional test circumstances, which comprised a temperature of 27±2 °C and a relative humidity of 65±2%, before the fabric characteristics were ascertained. The fabric was assessed for its performance and comfort properties.

Results and Discussion

Application of tea tree oil on cotton fabric Citric acid concentration: Four distinct citric acid concentrations, namely 5, 6, 7, and 8 percent (owf), were tested with an oil ratio of 1 to optimize the padding bath for the direct method. The optimum concentration of citric acid was determined by selecting the concentration with the lowest bending length and flexural rigidity and the highest crease recovery angle.

Table 1 presents data on the bending length, flexural rigidity, and crease recovery of cotton fabric samples treated with tea tree oil, at different concentrations of citric acid (5% to 8%).

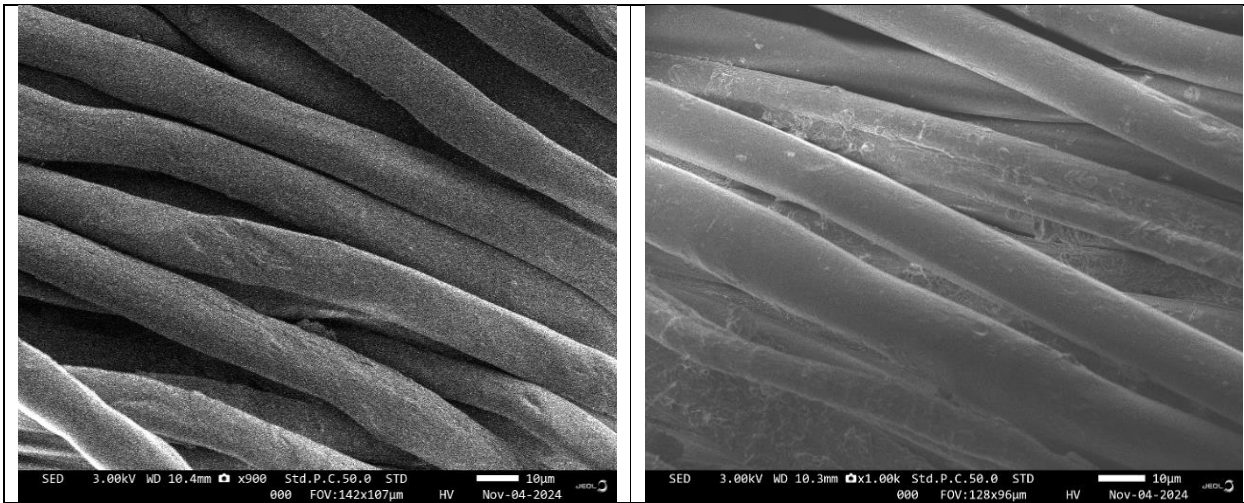
Table 1: Optimization of concentration of citric acid in padding bath for direct method

Oil	Concentration of citric acid (percent)	Parameter							Rank
		Bending length (cm)		Average bending length (cm)	Flexural rigidity (mg-cm)	Crease recovery (degree)		Average crease recovery (degree)	
		Warp	Weft			Warp	Weft		
Tea tree	5	3.29	2.58	2.93	28.51	78.18	75.93	77.05	II
	6	3.27	2.57	2.92	28.32	78.45	76.72	77.38	I
	7	3.38	2.62	2.98	28.89	77.69	75.72	76.70	III
	8	3.46	2.64	3.00	29.05	75.43	75.51	76.47	IV

The bending length values showed slight variations across different citric acid concentrations. For tea tree oil, the lowest bending length values (2.92 cm) appeared at 6% citric acid concentration. Across all concentrations, the values were consistent, with minor increases at higher concentrations. The lowest rigidity values were observed at 6% citric acid concentration i.e., 28.32 mg-cm. The fabric treated with 6% citric acid exhibited the best crease recovery highest average values (77.38°) for tea tree oil. The 5% and 7% treatments followed by the 8% citric acid concentration ranked lowest (IV) in terms of performance. The results suggested that 6% citric acid was the most effective concentration for maintaining fabric flexibility, reducing stiffness, and enhancing crease recovery. Therefore, 6 percent concentration of citric acid was optimized for direct application of tea tree oil on cotton fabric for mosquito repellent treatment.

Examination of treated fabric using Scanning Electron Microscopy (SEM)

The fabric sample treated directly by with tea tree oil was examined under SEM to know about their surface modification. The images clearly showed some residues of citric acid on the treated fabrics and it was inferred that the fibers modified after treatment with the oil directly.



Control sample | Direct method

Plate 1: SEM image of tea tree oil treated fabric

Evaluation of treated fabrics' mosquito repellency through cage test

The mosquito repellency of the treated fabric samples was assessed by comparing the number of mosquitoes repelled by the treated samples with those that settled on the untreated (control) samples.

The table 2 compares mosquito counts on an untreated control fabric (C) versus a repellent-treated fabric (T) at multiple observation times and reports repellency percentage (R%) for n = 50 mosquitoes per test. Higher R% means stronger repellent effect. The values were consistently high (94-100%), indicating the treated fabric markedly reduced mosquito landings throughout 24 hours.

Table 2: Efficacy of mosquito repellent treated fabrics n = 50

Observation time	C	T	R%
0 minute	48	2	96
15 minutes	47	3	94
30 minutes	48	2	96
45 minutes	48	2	96
60 minutes	47	3	96
2 hours	47	3	94
4 hours	47	3	94
6 hours	48	2	96
8 hours	48	2	96
24 hours	50	0	100

C-Number of mosquitoes on controlled sample, T-Number of mosquitoes on treated sample, R-Repellency percent

Immediately after treatment (0 minute) repellency is 96%, showing almost all mosquitoes avoided the treated fabric. Over the first 8 hours repellency stays at 94-96%, indicating durable short-term protection. At 24 hours repellency reaches 100% because all 50 mosquitoes avoided the treated sample while none were recorded on the treated fabric. The treated fabric provided strong and sustained repellency for at least 24 hours under the test conditions used. Consistently low T values and high R% suggested the repellent finish is effective and reasonably long-lasting.

Cone/toxicity test

The mortality rate of mosquitoes exposed to the treated fabric samples to determine the toxicity of the treated samples against the insecticide (mosquitoes) were assessed. The findings of the knockdown or mortality rates are tabulated in Table 3.

Table 3: Knockdown percentage of exposed mosquitoes

n-20

Treatment method	*Aedes aegypti*		*Anopheles stephensi*	
	Number of knockdowns	**KD %**	**Number of knockdowns**	**KD %**
Control sample	0	0	0	0
Direct	11	55	14	70

KD%-knockdown percentage, time of exposure of the specimen-3 minutes, observation time-24 hours

The table reports the number and percentage of mosquitoes knocked down after a 3-minute exposure and a 24-hour observation, for two species with n = 20 mosquitoes per treatment. Control sample produced 0 knockdowns and 0% KD for both species, confirming no background effect in the absence of treatment. Direct exposure produced moderate knockdown i.e., 55% for *Aedes aegypti* and 70% for *Anopheles stephensi*, showing the treatment causes substantially more immediate incapacitation in Anopheles than in Aedes under the same conditions. The difference suggests species-specific susceptibility to the tested treatment.

Assessment of the various characteristics of treated fabric

A comparison of the physical characteristics of two fabric samples treated fabric and a control sample is shown in table 4. A denser weave was indicated by a small increase in both warp and weft counts. This could decrease porosity and increase durability. The slightly thicker treated fabric may have an impact on its tactile feel, elasticity, or insulation. The cloth weight has increased by almost 10%, which is the most noticeable alteration. Fiber swelling, coatings, or chemical finishes could be the cause of this. By adding weight and density, the treatment seems to improve the fabric's structural stability. For applications like upholstery, industrial fabrics, or protective apparel that need for stronger, more resilient textiles, these modifications might be advantageous.

A thorough comparison of the performance characteristics of a treated fabric and a control fabric sample is shown in Table 5, emphasizing the ways in which treatment influences both mechanical and functional behaviour. Weft tearing and tensile strength are greatly increased by the treatment, which increases the fabric's durability throughout its width. The weft elongation increases, indicating directional flexibility, whereas the warp elongation decreases (stiffer). A harder hand feel is indicated by slight increases in flexural rigidity and bending length. Decline in crease recovery might have an impact on maintenance and appearance. The treatment had a mixed effect overall: certain recovery/elasticity metrics dropped, some strength and stiffness measures increased, and some dimensional/handle alterations were minor but noticeable.

Table 4: Preliminary properties of the treated fabric

Preliminary properties	Fabric count (ends and picks/inch)				Fabric thickness (mm)		Fabric weight (g/m^2)	
	Warp Mean ± S.E.	**Percent change**	**Weft Mean ± S.E.**	**Percent change**	**Mean**	**Percent change**	**Mean ± S.E.**	**Percent change**
Control sample	74.00±0.23	-	57.00±0.69	-	0.29	-	132.00±0.57	-
Treated fabric	76.00±0.45	+2.70	59.00±0.36	+3.51	0.30	+3.45	145.00±0.50	+9.85

The control and treated fabrics' comfort-related characteristics i.e., wickability (warp and weft), water absorbency (time), moisture regain (bulk hygroscopicity), and air permeability are tabulated in Table 6. Significantly faster water uptake and significantly increased wicking (particularly weft) at the same time suggest surface and inter-yarn changes that promote capillary transport, such as increased surface energy, the formation of fine capillary channels, finish redistribution into interstices, or fibre swelling that narrows channels and speeds up capillarity. Although liquid transfer on the surface is faster, the decreased moisture regain indicates that the treatment either decreased the hygroscopicity of bulk fibres or deposited a finish that reduces the fabric's capacity to collect and retain water vapor. Faster liquid transport and increased air permeability indicate that the treatment did not clog pores; instead, it may have rearranged the yarn packing or produced micro-pathways that facilitate the movement of both liquid and air.

Table 5: Performance properties of the treated fabric

Performance properties	Tearing strength (KGF)				Tensile strength (Kg)				Elongation (%)			
	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change
Control sample	3.10±0.054	-	2.70±0.005	-	23.40±0.006	-	12.15±0.080	-	11.96±0.008	-	16.49±0.006	-
Treated fabric	3.10±0.048	+0.00	3.60±0.008	+33.33	24.50±0.006	+4.70	20.30±0.006	+67.08	11.22±0.005	-6.19	20.37±0.003	+23.53
	Bending length (mm)				Crease recovery (degree)				Flexural rigidity (mg-cm)			
	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change	Mean ± S.E.		Percent change	
Control sample	3.26±.007	-	2.56±.007	-	82.57±.005	-	78.15±.013	-	23.95±.002		-	
Treated fabric	3.38±.009	+3.68	2.65±.006	+3.51	77.26±.003	-6.43	75.47±.003	-3.42	24.19±.01		+1.00	

Table 6: Comfort properties of the treated fabric

Comfort properties	Wick ability (cm)				Water absorbency (sec)		Moisture regain (%)		Air permeability ($m^3/m^2/min$)	
	Warp Mean ± S.E.	Percent change	Weft Mean ± S.E.	Percent change	Mean ± S.E.	Percent change	Mean ± S.E.	Percent change	Mean ± S.E.	Percent change
Control sample	1.60±0.004	-	0.50±0.005	-	<201	-	6.80±0.003	-	186.70±0.004	-
Treated fabric	1.92±0.003	+20.00	2.52±0.002	+404.00	<48	-76.12	6.12±0.004	-10.00	198.37±0.006	+6.25

Conclusion

Tea tree oil impregnation of cotton fabric resulted in a multipurpose textile with quantifiable improvements in mechanical, comfort, and physical characteristics in addition to significant mosquito-repellent activity. In addition to substantial improvements in weft-direction tensile, tearing strength, and elongation, treated samples also displayed increased fabric count, thickness, and weight, suggesting improved durability and toughness following treatment. The treatment resulted in a slight decrease in crease recovery and a slight increase in stiffness (bending length and flexural rigidity), indicating a trade-off between fabric hand and mechanical reinforcement. In terms of application, treated cotton works well for products that need enhanced durability and passive mosquito protection (such as camping textiles, bed nets, and outdoor clothing).

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