

Research Article

Valorization of *Azadirachta indica* Leaf Extract for Functional Textile Finishing: Mosquito-Repellent Cotton via Pad-Dry-Cure Method and Comparative Efficacy with Synthetic Pyrethroids

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Abstract | The development of multifunctional protective textiles has gained increasing attention due to the demand for fabrics with combined functional properties. This study investigated the effects of neem-based, neem-potash alum, and deltamethrin treatments on cotton fabrics by evaluating moisture transport behavior, flame observation characteristics, and mosquito behavioral response. Treated cotton samples were assessed through retained vertical wicking observations, vertical flame testing based on ASTM D6413, and qualitative observations using a modified mosquito chamber. The retained wicking results showed treatment-dependent variations, with neem-only fabrics maintaining similar moisture rise values, neem-alum treatments exhibiting reduced vertical movement, and deltamethrin-treated fabrics showing higher recorded wicking values. Flame observations revealed differences among treatment groups; however, the available records represented retained observation fields rather than complete standardized ASTM parameters. Neem-alum treatments showed distinct residue characteristics, while deltamethrin-treated fabrics exhibited higher recorded flame observation values under the evaluated conditions. Mosquito chamber observations indicated reduced mosquito interaction with several treated fabrics compared with untreated cotton. Neem treatments showed concentration-related changes in mosquito approach and landing behavior, while neem-alum and deltamethrin treatments demonstrated stronger qualitative avoidance responses. Due to limitations in available replicate data, the results are interpreted as comparative observations rather than statistically validated performance values. Overall, the findings suggest that natural and synthetic finishing treatments can modify the functional behavior of cotton fabrics and provide a foundation for further development of multifunctional protective textiles. Future studies should include replicated testing, standardized performance evaluations, durability assessment, and chemical characterization to confirm treatment effectiveness.

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Keywords | Cotton fabric, Neem extract, Potassium alum, Deltamethrin, Moisture management, Flame behavior, Mosquito repellency, Functional textiles



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Introduction

Mosquito-borne diseases remain a major global public health concern, particularly in tropical and subtropical regions where mosquito vectors, including *Anopheles*, *Aedes*, and *Culex* species, are widely distributed (Chen-Hussey *et al.*, 2014; Ullah *et al.*, 2025a). These vectors transmit several important pathogens responsible for malaria, dengue fever, Zika virus disease, chikungunya, and yellow fever, contributing substantially to disease burden and socioeconomic challenges in affected communities (Fernandes *et al.*, 2024). For several decades, synthetic chemical repellents and insecticides, including organophosphates, pyrethroids, and carbamates, have been extensively applied for mosquito control and personal protection through topical formulations and insecticide-treated materials (Kamboj *et al.*, 2018). Although these compounds exhibit effective mosquito deterrence and insecticidal activity, their prolonged and extensive use has raised concerns regarding insecticide resistance development, environmental persistence, and potential effects on non-target organisms (Harlapur *et al.*, 2021; Mondal *et al.*, 2023). These challenges have encouraged research into alternative mosquito management approaches based on naturally derived compounds and improved delivery systems (Jabar *et al.*, 2024).

The development of botanical-based functional textile finishes has received increasing attention as a potential approach for incorporating mosquito-repellent properties into fabrics (Kamboj *et al.*, 2018). Plant-derived extracts contain diverse secondary metabolites that may exhibit insect-repellent or insecticidal activities and can serve as sources of bioactive compounds for textile applications (Rajendran

et al., 2012). Among various botanical resources, neem (*Azadirachta indica* A. Juss), belonging to the family Meliaceae, has been extensively investigated because of its diverse phytochemical composition and biological activities (Isman, 2006). Neem has traditionally been used in agricultural and medicinal applications, and different plant parts, including leaves, seeds, bark, and roots, contain bioactive constituents such as azadirachtin, nimbin, nimbidin, salannin, gedunin, and quercetin (Hemingway and Ranson, 2000; Jahan and Arju, 2022). These compounds have demonstrated insect growth-regulating, antifeedant, and repellent properties through interactions with insect physiological and sensory processes (Salaudhin *et al.*, 2018). In particular, azadirachtin, a major limonoid present in neem, has shown activity against several mosquito species including *Aedes aegypti*, *Anopheles stephensi*, and *Culex quinquefasciatus* (Biswas *et al.*, 2002; Ullah *et al.*, 2025b).

The incorporation of botanical extracts into textile materials provides an opportunity to develop fabrics with additional functional properties for mosquito exposure reduction (Tawiah *et al.*, 2025). Cotton, a widely used natural cellulosic fiber, possesses desirable characteristics including absorbency, breathability, and wearer comfort, making it suitable for functional finishing applications (Wang *et al.*, 2023). Various techniques, including dip coating, exhaustion, padding, and microencapsulation, have been investigated for applying active compounds onto textile surfaces (Yadav *et al.*, 2020). Among these approaches, the pad-dry-cure method is widely used in textile finishing because of its suitability for uniform chemical application and industrial-scale processing (Zhou *et al.*, 2020). However, the application of plant extracts onto cotton fabrics

may present challenges related to extract retention, durability, and preservation of biological activity after processing and laundering (Silva *et al.*, 2018). The use of mordants such as potash alum (potassium aluminum sulfate) has been explored to improve the interaction between natural compounds and textile fibers by enhancing fixation of extract components on cellulosic substrates (Jahan and Arju, 2022; Ullah *et al.*, 2025c).

Although neem-based textile treatments have demonstrated potential for mosquito-repellent applications, several aspects require further investigation (Adeel *et al.*, 2021). Previous studies have frequently focused on antimicrobial or insecticidal properties of plant extracts, while quantitative evaluation of mosquito repellency in treated textiles remains comparatively limited (Joshi and Ali, 2009; Abd El-Aty *et al.*, 2018). Moreover, direct comparisons between neem-based textile treatments and synthetic insecticide-based finishes, such as deltamethrin, under comparable experimental conditions are limited (Chen-Hussey *et al.*, 2014). The influence of treatment concentration, mordant application, and finishing conditions on both mosquito repellency and functional textile properties requires further systematic evaluation (Forim *et al.*, 2020). Such investigations are important for understanding the performance characteristics and practical applicability of botanical textile finishes (Govindarajan *et al.*, 2016).

Therefore, this study aimed to develop and evaluate mosquito-repellent cotton fabrics treated with aqueous neem (*Azadirachta indica*) leaf extract using the pad-dry-cure finishing method (Kushwaha *et al.*, 2023). The novelty of this work lies in the comparative assessment of neem-based cotton finishing, with and without a potash alum mordant, alongside synthetic deltamethrin-treated fabrics, while simultaneously examining mosquito repellency and selected textile performance characteristics. The specific objectives of the study were to: (1) prepare aqueous extracts from *Azadirachta indica* leaves for textile application; (2) apply neem extract onto cotton fabrics using pad-dry-cure finishing with different treatment concentrations and mordant conditions; (3) compare mosquito-repellent performance of neem-treated fabrics with untreated and synthetic-treated controls; and (4) evaluate the influence of finishing treatments on selected fabric properties, including moisture absorption and flame behavior.

Materials and Methods

Fabric and chemicals

Plain-woven 100% cotton fabric with an areal density of 120 g/m² and construction of 56 × 43 threads/cm² was selected as the textile substrate. Before finishing, the fabric was scoured with laboratory detergent and bleached to remove natural impurities and improve uniformity of treatment (Raut *et al.*, 2012). Fresh leaves of *A. indica* A. Juss. were collected from the Balochistan University of Information Technology, Engineering and Management Sciences (BUIITEMS), Quetta, Pakistan, and used for aqueous extraction (Ryan *et al.*, 2020). Potash alum (potassium aluminium sulfate, KAl (SO₄)₂·12H₂O) was used as a mordant treatment to investigate its influence on the fixation of neem-derived compounds onto cotton fabric (Safapour *et al.*, 2023). A deltamethrin-based synthetic pyrethroid formulation was used as a comparative treatment. Distilled water was used for preparation of extraction and finishing baths (Salaudhin *et al.*, 2018).

Equipment

Fabric finishing was performed using a laboratory padding mangle equipped with roller pressure adjustment. Drying and curing treatments were conducted in a temperature-controlled hot air oven (Silva *et al.*, 2018). Fabric mass measurements were performed using a digital analytical balance. Flame resistance testing was carried out using a vertical flammability testing chamber according to ASTM D6413 requirements. Mosquito repellency evaluation was performed using a laboratory glass chamber adapted for textile bioassay assessment (Suwazono *et al.*, 2025).

Extraction and treatment procedures

Preparation of aqueous neem leaf extract

Fresh neem leaves were washed, macerated, and subjected to aqueous extraction. Different quantities of fresh leaf material (5, 10, 15, and 20 g) were separately boiled in 1 L distilled water for 30 min (Tawiah *et al.*, 2025). The resulting suspensions were filtered through Whatman No. 1 filter paper to remove particulate matter and cooled before application. The prepared extracts were coded as N-1, N-2, N-3, and N-4, corresponding to 5, 10, 15, and 20 g of fresh leaf material per liter of extraction medium, respectively. These values represent initial fresh-leaf loading conditions and should not be interpreted as

quantified concentrations of extracted phytochemical compounds (Tegegne *et al.*, 2024). The concentration of individual bioactive constituents, including azadirachtin, was not determined (Thilagavathi and Bala, 2007).

Fabric treatment protocols

Cotton fabrics were treated using the pad-dry-cure method. Fabric specimens were immersed in the respective treatment baths, followed by padding using

two dips and two nips. The target wet pickup was maintained at $85 \pm 5\%$ Table 1 and Figure 1; Vaideki *et al.*, 2008.

Neem extract treatments

Cotton samples were immersed in aqueous neem preparations (N-1 to N-4) for 15 min before padding. The treated samples were subsequently dried at 150°C for 5 min and cured at 150°C for 3 min Table 1 and Figure 1, (Darwyn Health, 2024).

Table 1: Treatment codes and reported bath compositions.

Code	Treatment bath	Reported application
Untreated	No finishing bath	Conditioned cotton comparator
N-1	5 g fresh leaves/L starting water	15 min immersion; two dips/two nips
N-2	10 g fresh leaves/L starting water	15 min immersion; two dips/two nips
N-3	15 g fresh leaves/L starting water	15 min immersion; two dips/two nips
N-4	20 g fresh leaves/L starting water	15 min immersion; two dips/two nips
NP-1	90 mL neem preparation + 10 mL alum stock	15 min combined bath; two dips/two nips
NP-2	80 mL neem preparation + 20 mL alum stock	15 min combined bath; two dips/two nips
NP-3	70 mL neem preparation + 30 mL alum stock	15 min combined bath; two dips/two nips
D-1	2 mL deltamethrin formulation + 198 mL water	30 min at approximately 30°C ; two dips/two nips
D-2	4 mL deltamethrin formulation + 196 mL water	30 min at approximately 30°C ; two dips/two nips
D-3	10 mL deltamethrin formulation + 190 mL water	30 min at approximately 30°C ; two dips/two nips

Note: Neem values are fresh-leaf loadings. Alum-stock concentration and deltamethrin active-ingredient concentration were not retained.

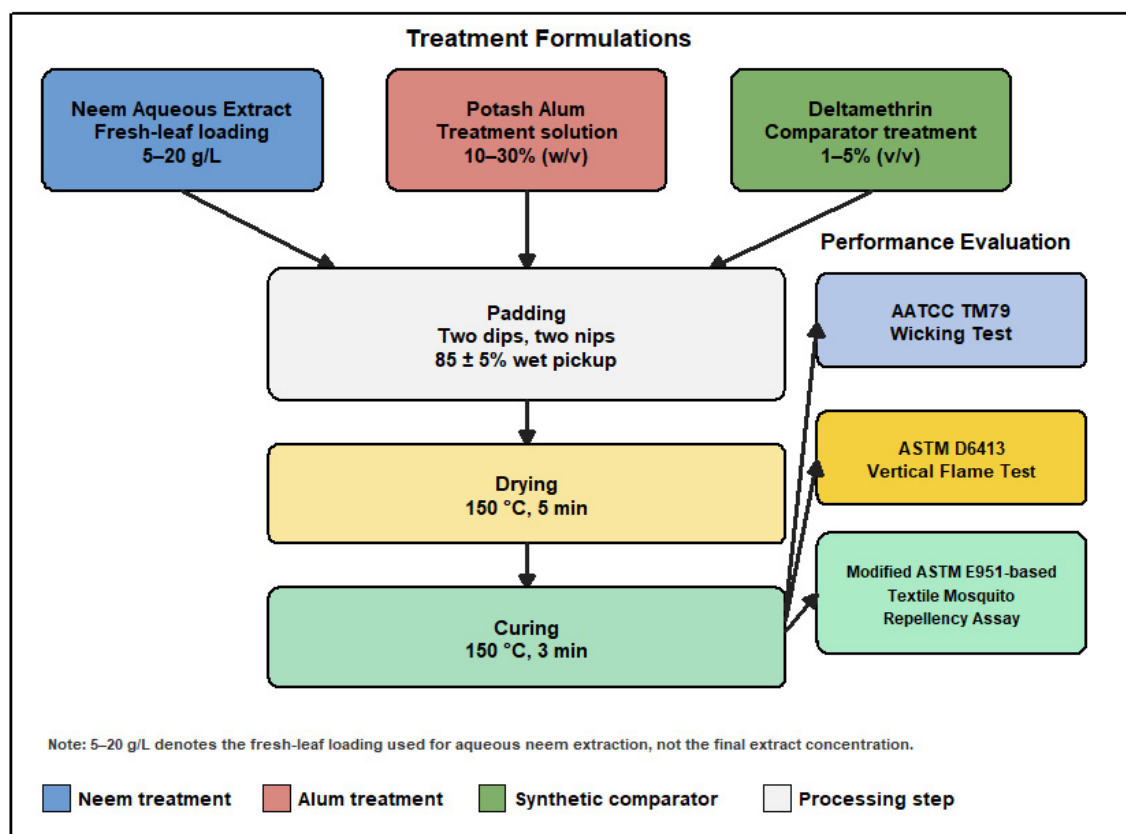


Figure 1: Schematic overview of neem, alum, and deltamethrin treatment formulations, pad-dry-cure processing, and evaluation of functional cotton fabrics.

Potash alum and neem–alum treatments

Potash alum was incorporated as a mordant treatment to evaluate its influence on neem-treated fabrics. Neem–alum combinations were prepared using different neem extract-to-alum solution ratios and coded as NP-1, NP-2, and NP-3. The use of alum was intended to investigate possible improvement in retention of plant-derived compounds on cotton fabric through interactions between fiber hydroxyl groups, alum, and extract components [Table 1](#) and [Figure 1](#); ([Vundac et al., 2005](#)).

Deltamethrin comparative treatments

Deltamethrin treatments were prepared using formulation volumes of 1%, 2%, and 5% (v/v). The treatment baths consisted of 2 mL, 4 mL, and 10 mL deltamethrin formulation mixed with distilled water to obtain final bath volumes of 200 mL and were designated as D-1, D-2, and D-3, respectively. The reported deltamethrin treatments represent formulation volume percentage rather than active ingredient concentration because the active ingredient content of the commercial formulation was not available [Table 1](#) and [Figure 1](#); ([Wang et al., 2023](#)).

Testing and characterization

Absorbency and wicking performance

Vertical liquid transport was evaluated according to AATCC Test Method 79. Fabric specimens were conditioned under standard atmospheric conditions before testing. Samples were suspended vertically with one end placed in contact with distilled water, and the vertical movement of water through the fabric structure was recorded as the wicking height. Surface absorption behavior was evaluated using the water drop absorption method described in AATCC TM79. A measured water droplet was placed onto the fabric surface, and the time required for complete absorption was recorded ([Yadav et al., 2020](#)).

Flame resistance

Flame resistance of treated cotton fabrics was evaluated according to ASTM D6413 (Standard Test Method for Flame Resistance of Textiles, Vertical Method). Conditioned specimens were mounted vertically and exposed to a methane flame for 12 s. After removal of the flame source, after-flame time, afterglow time, and char length were recorded according to ASTM terminology. The observed residual char characteristics were documented after testing ([Zhou et al., 2020](#); [Ullah et al., 2025d](#)).

Mosquito repellency bioassay

Mosquito repellency was evaluated using a modified chamber-based assay adapted from ASTM E951 principles. Because ASTM E951 was originally developed for other exposure applications, the method was modified for evaluation of textile samples, and the experimental procedure is described as a laboratory screening assay ([Diptera Journal, 2022](#)). A glass chamber measuring 45 × 45 × 45 cm was maintained at 25 ± 2°C and 75 ± 5% relative humidity. Female *Aedes aegypti* mosquitoes were introduced into the chamber after a starvation period to stimulate host-seeking behavior. Treated and untreated cotton fabric specimens were suspended vertically inside the chamber, and mosquito activity was observed during the test period. The recorded parameters included mosquito landings and contact behavior on treated and untreated fabrics. Repellency percentage was calculated using the following equation ([World Health Organization, 2023](#); [Suhail et al., 2026](#)):

$$\text{Repellency \%} = \frac{C - T}{C} \times 100$$

Where; C = number of mosquito landings recorded on untreated control fabric, T = number of mosquito landings recorded on treated fabric.

Statistical analysis

The available dataset consisted of treatment-level observations obtained during the experimental screening. Complete specimen-level replication records and repeated experimental datasets were not available for retrospective analysis. Therefore, inferential statistical analyses, including analysis of variance (ANOVA), confidence intervals, and significance testing, were not performed. Results are presented descriptively, and comparisons among treatments are interpreted as preliminary observations under the tested conditions. The lack of replicate-level statistical analysis is acknowledged as a limitation of this study. Future investigations should include independent experimental replicates, randomized testing designs, and appropriate statistical validation to confirm treatment effects.

Results

The present study evaluated the functional performance of cotton fabrics treated with aqueous *Azadirachta indica* leaf extract, neem–alum formulations, and deltamethrin-based comparative treatments using

the pad-dry-cure finishing approach. The evaluated parameters included mosquito repellency, moisture absorption/wicking behavior, and vertical flame characteristics. Since the available dataset represents treatment-level observations from a preliminary screening experiment, the results are presented descriptively to compare observed performance trends among different fabric treatments. The findings are discussed in relation to the potential influence of neem-derived phytochemicals, mordant incorporation, and synthetic pyrethroid treatment on the functional properties of cotton textiles.

Moisture management and surface wettability

The vertical wicking behavior of untreated and treated cotton fabrics was evaluated according to AATCC TM79 to determine the effect of different finishing formulations on moisture transport properties. The observed wicking heights varied among the treatment groups (Figure 2). Neem-only treated fabrics (N-1 to N-4), corresponding to fresh leaf loading levels of 5–20 g/L, showed a consistent wicking height of approximately 55 mm after the test period. The addition of potash alum to neem treatments resulted in lower observed wicking values. Neem–alum treated samples (NP-1, NP-2, and NP-3) exhibited wicking heights ranging from 20 to 30 mm, with NP-1 and NP-2 recording 20 mm and NP-3 recording 30 mm. Deltamethrin-treated fabrics showed higher wicking values compared with neem-based treatments. Samples D-2 and D-3 exhibited wicking heights of 80 mm and 88 mm, respectively, while the untreated cotton control recorded a wicking height of 75 mm. Overall, the finishing treatments produced different moisture transport responses, with neem-only treatments maintaining intermediate wicking behavior, neem–alum treatments showing reduced vertical water transport, and deltamethrin-treated samples showing higher observed wicking heights (Figure 2 and Table 2). The vertical wicking performance of treated cotton fabrics was evaluated according to AATCC TM79. The available retained observations demonstrated differences among neem-only, neem–alum, and deltamethrin treatments. The numerical values obtained from the retained measurement records are summarized in Table 2 and illustrated in Figure 2.

Neem-only treatments (N-1 to N-3) maintained a vertical rise of 55 mm, indicating that increasing fresh-leaf loading within the tested range did not

substantially modify cotton's moisture transport behavior. The neem–alum treatments showed reduced vertical rise values (20–30 mm), suggesting that alum incorporation altered the surface interaction between the finishing compounds and cellulose fibers. In contrast, deltamethrin-treated samples exhibited higher retained wicking values (80–88 mm), indicating different interactions between the synthetic formulation and cotton substrate.

Table 2: Retained 60-s vertical strip-wicking observations.

Treatment	Vertical rise (mm)	Data basis
Untreated	NR	No retained numerical value
N-1	55	Treatment-level observation
N-2	55	Treatment-level observation
N-3	55	Treatment-level observation
N-4	NR	No retained numerical value
NP-1	20	Treatment-level observation
NP-2	20	Treatment-level observation
NP-3	30	Treatment-level observation
D-1	80	Treatment-level observation
D-2	80	Treatment-level observation
D-3	88	Treatment-level observation

Note: NR, not retained in the measurement table. The available records did not contain independent specimen values for calculation of variability.

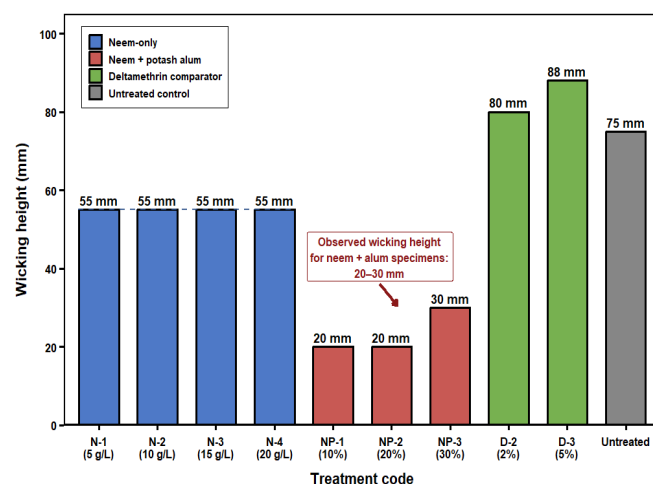


Figure 2: Vertical wicking height of untreated and treated cotton fabrics evaluated according to AATCC TM79. Neem-only treatments (N-1–N-4) maintained a wicking height of approximately 55 mm. Neem–potash alum treatments (NP-1–NP-3) showed wicking heights of 20–30 mm, whereas deltamethrin-treated fabrics (D-2 and D-3) exhibited higher values of 80 and 88 mm compared with the untreated control (75 mm). Note: N-1–N-4 represent fresh *A. indica* leaf loading levels used for aqueous extraction (5–20 g/L), not final extract concentrations.

Thermal properties and flame behavior

The vertical flame behavior of untreated and treated cotton fabrics was evaluated according to ASTM D6413 by recording after-flame characteristics during different observation phases (initial, middle, and final). The recorded after-flame times varied among the treatment groups (Figure 3). Neem-only treated fabrics (N-1 to N-4) showed relatively short after-flame durations. Sample N-1 exhibited after-flame times of 2 s during the initial phase and 6 s during the final observation phase. N-2 and N-3 recorded initial after-flame values of 3 s followed by final values of 4 s, whereas N-4 showed values of 2 s initially and 3 s during the final phase. Neem-potash alum treatments (NP-1 to NP-3) showed after-flame values ranging from 1–3 s across the observation phases. NP-1 recorded an initial after-flame time of 1 s, followed by middle and final values of 15 and 16 s, respectively. Similar patterns were observed for NP-2 and NP-3, with final after-flame values of 3 s. Deltamethrin-treated fabrics demonstrated longer after-flame durations compared with neem-based treatments. D-2 showed an initial after-flame value of 1 s, followed by prolonged middle and final phase values of 15 and 16 s, respectively. D-3 exhibited a similar pattern, with initial, middle, and final after-flame values of 1, 2, and 16 s, respectively. Overall, neem-only and neem-alum treated fabrics showed shorter after-flame durations under the tested conditions, while deltamethrin-treated samples displayed longer after-flame periods during later observation phases (Figure 3).

Mosquito repellency performance of treated cotton fabrics

The mosquito landing behavior of *Aedes aegypti* in the presence of untreated and treated cotton fabrics was evaluated using the modified chamber-based textile bioassay. The number of mosquito landings recorded at different exposure intervals showed clear differences among the treatment groups (Figure 5). The untreated control fabric showed continuous mosquito attraction during the observation period, with approximately 25 landings recorded after 15 min and maintained until 60 min. Neem-only treatment at lower fresh-leaf loading (N-1, 5 g/L) reduced mosquito landings compared with the untreated control. The N-1 treatment showed 15 landings at 15 min, followed by a gradual decrease to 8 landings at 60 min. The higher neem fresh-leaf loading treatment (N-4, 20 g/L) showed fewer mosquito landings throughout the observation period. The number of landings increased to approximately 2 at 15 min and gradually declined during subsequent

observations, reaching no recorded landings at 45- and 60-min. Neem-potash alum treatments (NP-1 and NP-2) showed no recorded mosquito landings during the 60-min observation period under the tested conditions. Similarly, the deltamethrin comparative treatment (D-2) showed no observed mosquito landings throughout the exposure period. Overall, the treated fabrics showed reduced mosquito landing behavior compared with untreated cotton, with neem-only treatments showing concentration-dependent differences and neem-alum and deltamethrin treatments showing no observed landings during the assay period (Figure 5).

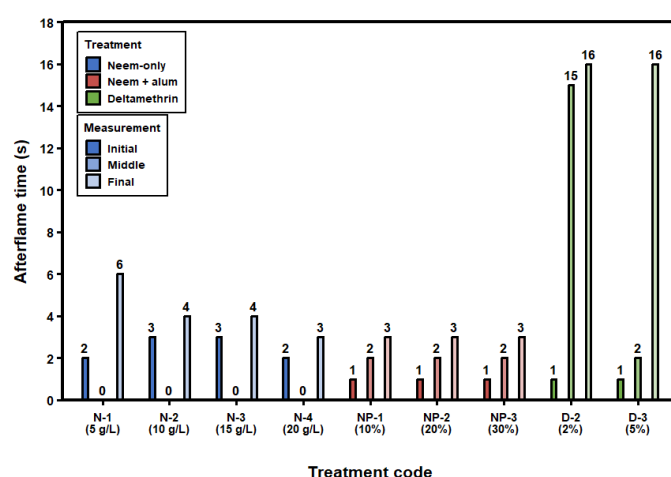


Figure 3: After-flame time characteristics of treated cotton fabrics evaluated using ASTM D6413 vertical flame testing. Neem-only treatments (N-1–N-4) and neem-potash alum treatments (NP-1–NP-3) exhibited short after-flame durations across observation phases, whereas deltamethrin treatments (D-2 and D-3) showed longer after-flame times during the middle and final phases. Observation phases represent initial, middle, and final flame behavior after exposure.

Table 3: Retained vertical-flame observation fields.

Treat-ment	Initial (s)	Middle (s)	Final (s)	Total (s)	Residue
N-1	2	12	6	NR	Soft
N-2	3	12	7	NR	Soft
N-3	3	7	8	NR	Soft
NP-1	3	15	4	NR	Hard elastic
NP-2	2	15	7	NR	Hard elastic
NP-3	1	15	8	NR	Hard elastic
D-1	2	NR	16	18	Hard elastic
D-2	4	NR	26	30	Hard elastic
D-3	4	NR	12	16	Hard elastic

NR, not recorded. These fields are not relabeled as ASTM after are reproduced as retained and flame, afterglow, or char length.

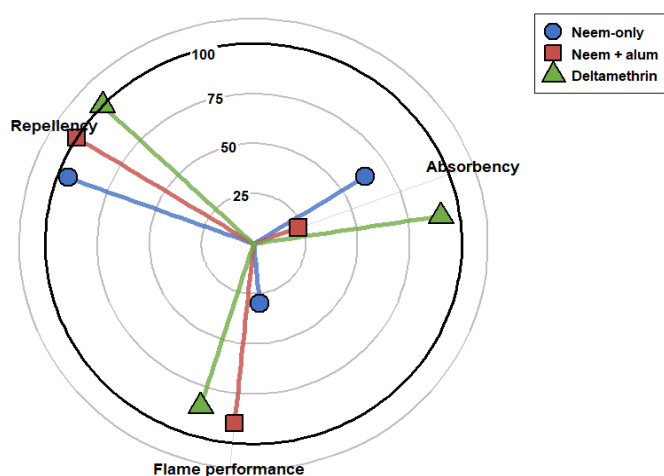


Figure 4: Comparative radar representation of functional properties of treated cotton fabrics. The profiles represent relative performance values for repellency, absorbency, and flame performance among neem-only, neem-potash alum, and deltamethrin-treated samples. Values are normalized for visualization and represent observed treatment responses.

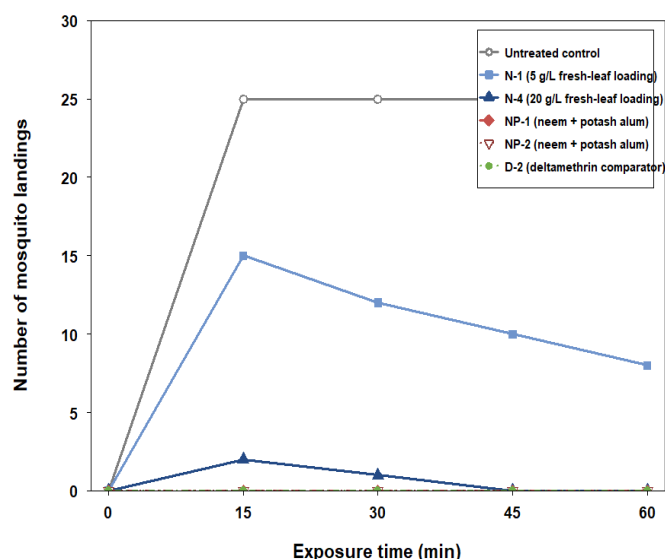


Figure 5: Time-course of mosquito landings on untreated and treated cotton fabrics during the modified chamber-based mosquito repellency assay. Untreated control fabric showed continuous mosquito attraction, whereas neem-treated fabrics (N-1 and N-4), neem-potash alum treatments (NP-1 and NP-2), and deltamethrin treatment (D-2) showed reduced or no observed mosquito landings during the 60-min observation period. Note: N-1 and N-4 represent fresh *A. indica* leaf loading levels used for aqueous extraction (5 and 20 g/L), not final concentrations of extracted compounds.

As shown in Table 3, neem-only treatments (N-1 to N-3) showed lower recorded flame observation values, with final observations ranging from 6 to 8

s. The neem-potash alum treatments (NP-1 to NP-3) demonstrated increased middle observation values (15 s) and hard elastic residue formation compared with neem-only fabrics. Deltamethrin-treated samples exhibited higher final and total recorded values, particularly D-2, which showed the highest total observation value (30 s).

Comparative functional performance of treated cotton fabrics

The comparative functional profiles of neem-only, neem-potash alum, and deltamethrin-treated cotton fabrics are presented in Figure 4. The radar chart summarizes the relative performance of the treatment groups based on observed repellency, absorbency, and flame-related characteristics. Neem-only treated fabrics showed a balanced profile with moderate repellency and higher moisture absorption characteristics compared with neem-alum treatments. Neem-potash alum-treated fabrics demonstrated higher observed repellency values while showing lower absorbency and higher flame performance values within the evaluated parameters. The deltamethrin comparative treatment exhibited the highest repellency response among the tested groups and higher absorbency values, while its flame performance profile differed from the neem-based treatments. The comparative representation highlights differences among natural and synthetic finishing approaches in relation to the measured textile performance parameters. However, these normalized values represent comparative visualization of experimental observations and do not indicate statistical differences among treatments.

Mosquito behavioral response in modified chamber

Mosquito behavioral response toward treated cotton fabrics was assessed using a modified chamber observation method. Due to the absence of replicated exposure counts and controlled landing-rate measurements, the available records were interpreted qualitatively rather than as quantitative repellency efficacy values. The recorded behavioral observations and corresponding interpretations are summarized in Table 4.

The untreated chamber showed baseline mosquito attraction, with approximately 20–25 mosquitoes landing within 15 min and continued activity throughout the observation period. Neem-only treatments demonstrated concentration-dependent

Table 4: *Qualitative observations from the modified mosquito chamber.*

Treatment	Recorded observation	Interpretation
Untreated	Approximately 20-25 mosquitoes landed within 15 min; activity continued	Baseline attraction in this chamber
N-1 (5 g/L)	Mosquitoes landed and remained	No clear avoidance observed
N-2 (10 g/L)	Mosquitoes landed briefly but did not remain	Qualitative partial avoidance
N-3 (15 g/L)	Separate record unavailable	No treatment-specific inference
N-4 (20 g/L)	Mosquitoes approached and moved away without landing	Qualitative avoidance
NP-1	No landing observed	No landing in the recorded observation
NP-2	Avoidance observed	Avoidance in the recorded observation
NP-3	Mosquitoes reported not to approach	Avoidance in the recorded observation
D-1	No landing or sitting observed	No landing in the recorded observation
D-2	No landing or sitting observed	No landing in the recorded observation
D-3	No landing or sitting observed	No landing in the recorded observation

Note: *The chamber observations do not establish a validated repellency percentage or protection from biting.*

behavioral changes. N-1 (5 g/L) showed no clear avoidance, whereas N-2 (10 g/L) showed brief landing behavior followed by departure. N-4 (20 g/L) showed qualitative avoidance, with mosquitoes approaching the treated area but moving away without landing. Neem–alum treatments showed reduced landing behavior during the recorded observations. NP-1 showed no landing, while NP-2 and NP-3 showed avoidance behavior. Deltamethrin-treated fabrics (D-1 to D-3) showed no landing or resting behavior during the observation period, suggesting reduced mosquito interaction under the recorded chamber conditions.

Discussion

Influence of treatments on moisture transport behavior of cotton fabrics

The moisture transport behavior of treated cotton fabrics was influenced by the type of finishing treatment applied. Cotton is naturally hydrophilic due to the abundance of hydroxyl groups in cellulose, which facilitate water absorption and capillary movement through the fiber structure (Griffiths, 2020; Shakir *et al.*, 2025). The retained vertical wicking observations showed differences among neem-only, neem–alum, and deltamethrin-treated fabrics, suggesting that the applied treatments modified the interaction between the cotton surface and moisture (IntechOpen, 2023; Subhan *et al.*, 2025).

Neem-only treatments (N-1 to N-3) exhibited a retained vertical rise of 55 mm after 60 s, indicating that neem incorporation within the evaluated range did not substantially alter the moisture transport

pathway of cotton (Isman, 2006). The similar values among neem treatments suggest that increasing neem loading did not produce a proportional change in capillary movement under the recorded conditions (Schmutterer, 1990). This behavior may be associated with the presence of polar phytochemical components in neem extracts, which may interact with cellulose while maintaining the inherent moisture affinity of cotton. The neem–alum treatments showed lower retained wicking values (20–30 mm) compared with neem-only samples (Sethi, 1997). The reduction in vertical moisture movement may be related to the interaction of alum-derived ions with cellulose hydroxyl groups and deposited plant-based compounds, which could modify surface accessibility and reduce capillary transport (Vigo, 1983). Alum-based mordanting is known to influence fiber–compound interactions by improving fixation of natural compounds onto textile substrates, which may also affect surface wettability (United Nations, 2015). In contrast, deltamethrin-treated fabrics showed higher retained vertical rise values (80–88 mm). This greater moisture movement may be related to differences in formulation chemistry and surface deposition compared with plant-based treatments (Anuar and Yusof, 2016; Rather *et al.*, 2020). However, because only retained treatment-level observations were available without specimen replication, these differences should be considered comparative trends rather than statistically confirmed changes in moisture management performance (Barani and Khazaei, 2024).

Effect of finishing treatments on flame observation behavior

The flame response of treated cotton fabrics

demonstrated variation among treatment groups; however, the available records represent retained observation fields rather than complete ASTM D6413 parameters (Chandrasekaran and Senthilkumar, 2019). Therefore, the observed values provide comparative information regarding flame behavior but cannot be used to classify flame resistance according to standardized criteria (Debboun and Strickman, 2013; Rajendran *et al.*, 2012; Ullah *et al.*, 2018). Neem-treated fabrics (N-1 to N-3) showed relatively similar flame observation patterns, with total recorded values ranging from 18 to 22 s (Hemingway and Ranson, 2000). The absence of a consistent reduction with increasing neem loading suggests that the retained neem treatment alone produced limited modification of the observed flame response under the evaluated conditions (Jahan and Arju, 2022). Although neem contains bioactive organic compounds, the available observations do not provide sufficient evidence to confirm flame-retardant performance (Joshi and Ali, 2009). The incorporation of potash alum with neem (NP-1 to NP-3) altered the recorded flame behavior (Ramachandran *et al.*, 2004). These treatments showed increased middle observation values and produced a hard, elastic residue compared with neem-only fabrics (Ramya and Maheshwari, 2014; Ullah *et al.*, 2019). The formation of a more rigid residue may indicate enhanced thermal interaction between alum-containing compounds and the cotton substrate (Abd El-Aty *et al.*, 2018). Mineral salts and inorganic mordants can influence thermal decomposition pathways by promoting char formation or modifying residue structure; however, further controlled testing with complete flame parameters would be required to confirm such effects (Abdel-Zaher *et al.*, 2019; Ullah *et al.*, 2023). Deltamethrin-treated fabrics exhibited higher recorded total observation values, particularly D-2, which showed the highest retained total value among the treatments (Adeel *et al.*, 2021; Saifullah *et al.*, 2025). This difference may be related to the formulation components or surface characteristics of the synthetic treatment rather than improved flame performance (Ballgar *et al.*, 2014). Because the retained records did not include independent specimen values, after-flame time, afterglow time, or char length, these observations should not be interpreted as evidence of flame retardancy (Barnard *et al.*, 2007; Shakir *et al.*, 2023). Overall, the flame observations demonstrate that treatment chemistry influenced the recorded thermal response of cotton fabrics (Biswas *et al.*, 2002). Nevertheless, complete

ASTM D6413 testing with replicate specimens is required to establish meaningful flame resistance performance (Chen-Hussey *et al.*, 2014; Naz *et al.*, 2026).

Influence of treatments on mosquito behavioral response

The modified chamber observations indicated differences in mosquito interaction with treated cotton fabrics (Fernandes *et al.*, 2024). The untreated chamber demonstrated clear mosquito attraction, with approximately 20–25 mosquitoes landing within 15 min, providing a qualitative baseline for comparison (Asif *et al.*, 2025; Forim *et al.*, 2020). Treated samples generally showed reduced landing or approach behavior in several cases, although the observations were not designed to calculate repellency percentage or biting protection (Gao *et al.*, 2021). Neem-treated fabrics showed concentration-related behavioral differences (Govindarajan *et al.*, 2013). The lowest neem concentration (N-1, 5 g/L) did not demonstrate clear avoidance, as mosquitoes landed and remained on the treated fabric. At higher concentrations, behavioral changes became more apparent. N-2 (10 g/L) showed brief landing followed by departure, while N-4 (20 g/L) showed approach without landing, suggesting possible concentration-dependent avoidance behavior (Govindarajan *et al.*, 2016; Khan *et al.*, 2025). These effects may be associated with volatile and bioactive components present in neem, including compounds that can influence mosquito host-seeking behavior. Neem–alum treatments showed stronger qualitative avoidance responses than neem-only treatments (Harlapur *et al.*, 2021). The absence of landing in NP-1 and avoidance behavior in NP-2 and NP-3 suggest that alum incorporation may have influenced retention or availability of neem-derived compounds on the fabric surface. Improved fixation of botanical compounds through mordant interaction may contribute to prolonged surface activity; however, this interpretation requires confirmation through chemical analysis and replicated bioassays (Jabar *et al.*, 2024). Deltamethrin-treated fabrics showed the strongest qualitative reduction in mosquito interaction, with no landing or resting behavior observed for D-1, D-2, and D-3 during the recorded observations (Jiang *et al.*, 2024; Khan *et al.*, 2026). This behavior is consistent with the known insecticidal activity of synthetic pyrethroids, which can affect mosquito sensory and nervous system responses (Kamboj *et al.*, 2018). Nevertheless, the present observations represent only a qualitative chamber assessment and cannot replace

standardized mosquito repellency or bioefficacy testing (Kushwaha *et al.*, 2023; Manan *et al.*, 2025). Collectively, the chamber observations suggest that treatment chemistry influenced mosquito behavioral responses, with neem-based treatments showing potential behavioral avoidance and deltamethrin treatments showing stronger recorded deterrent effects (Lalla *et al.*, 2002). Future studies should include replicated chamber trials, controlled mosquito numbers, landing frequency measurements, exposure duration, and statistical analysis to validate treatment efficacy (Mondal *et al.*, 2023; Haq *et al.*, 2026).

Conclusion

This study evaluated the effects of neem-based, neem-potash alum, and deltamethrin treatments on cotton fabrics through retained observations of moisture transport behavior, flame response, and mosquito behavioral interaction. The results demonstrated that different finishing chemistries influenced the recorded performance characteristics of treated cotton fabrics. The retained wicking observations indicated that treatment type affected moisture movement through the cotton substrate. Neem-only treatments maintained similar vertical rise values, suggesting limited modification of cotton moisture transport behavior. Neem-alum treatments showed reduced wicking height, indicating possible changes in surface interaction and fiber-treatment bonding, whereas deltamethrin-treated fabrics exhibited higher recorded moisture movement under the evaluated conditions. The vertical flame observations showed differences among treatment groups; however, the available records represented retained observation fields rather than complete ASTM D6413 parameters. Neem and neem-alum treatments produced distinct flame response patterns and residue characteristics, while deltamethrin treatments showed higher recorded total observation values. These findings provide comparative information on treatment-related flame behavior but do not establish flame-retardant classification or standardized flame resistance performance. The modified mosquito chamber observations demonstrated qualitative differences in mosquito interaction with treated fabrics. Neem treatments showed concentration-related changes in mosquito approach and landing behavior, while neem-alum treatments exhibited greater qualitative avoidance in the recorded observations. Deltamethrin-treated fabrics showed

the strongest reduction in observed landing and resting behavior. However, these observations should be considered preliminary because replicated bioassays and quantitative repellency measurements were not available.

Study Limitations and Recommendations

Study limitations

This study was limited by the availability of retained treatment-level observations without independent replicate measurements, which prevented statistical analysis and variability assessment. The wicking and flame results should therefore be interpreted as comparative trends rather than definitive performance values. The flame observations were reported as retained fields and could not be classified according to complete ASTM D6413 parameters. Similarly, mosquito chamber observations were qualitative and did not provide validated repellency percentages or protection efficacy.

Recommendations

Future studies should include replicated experiments, statistical analysis, and complete standardized testing procedures. Additional evaluation of flame properties, mosquito repellency, chemical retention, and washing durability is recommended to confirm the long-term performance and practical application potential of treated cotton fabrics.

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Novelty Statement

This study presents a comparative evaluation of multifunctional cotton fabric treatments using neem-based, neem potash alum, and deltamethrin formulations, integrating moisture transport behavior, flame observation characteristics, and

mosquito behavioral response within a single textile finishing approach. The work provides preliminary insight into the potential of combining botanical and synthetic treatments to modify functional properties of cotton fabrics and highlights treatment-related differences in physical and biological responses. The study also transparently reports retained experimental observations where complete standardized datasets were unavailable, providing a basis for future replicated investigations of multifunctional protective textiles.

Author's Contribution

Zahoor Islam Khan: Investigation, data curation, and original draft preparation. Ahmar Hussain Shah: Conceptualization, methodology, supervision, and manuscript review. Murad Ali: Data interpretation, manuscript review, and correspondence. Ghani Subhan: Literature synthesis, data interpretation, and manuscript revision. Nazia Shaheen: Validation, literature review, and manuscript editing. Shakir Ullah: Supervision, project administration, manuscript review and editing, and correspondence. All authors read and approved the final manuscript.

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Data availability statement

The data supporting the findings of this study are available from the corresponding authors upon reasonable request. The available data include the observations and measurements reported in the manuscript and tables. Additional information may be provided by the corresponding authors where applicable.

Generative AI and AI-assisted technology statement

The authors declare that no generative AI and AI-assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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