

VOLUME 1
ISSUE 4
OCTOBER–DECEMBER
2026



P - ISSN: 3116-3807



E - ISSN: 3116-3815

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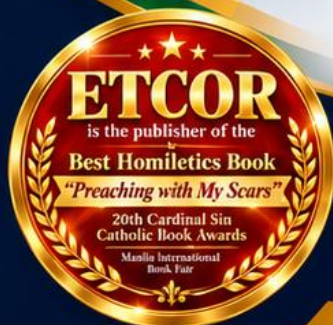
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Development and performance evaluation of bio-based mosquito coils from different plant parts of citronella grass (*Cymbopogon nardus*)

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Received: 01 September 2026

Revised: 04 September 2026; 03 October 2026; 09 October 2026

Accepted: 15 October 2026

Available Online: 16 October 2026

Volume 1 (2026), Issue 4, P-ISSN – 3116-3807; E-ISSN - 3116-3815

<https://doi.org/10.63498/injeni9>

Abstract

Aim: This study developed and evaluated bio-based mosquito coils made from citronella grass (*Cymbopogon nardus*) plant parts as a locally available alternative to synthetic coils. It assessed flammability, burning time, mosquito knockdown response, and final recorded mortality of *Anopheles* mosquitoes.

Methodology: Four formulations were tested: a transfluthrin control and coils made from citronella leaves, pseudostem, and roots. The botanical formulations contained citronella plant material, neem and coconut shell charcoal powders, citronella-infused cooking oil, and cassava starch paste. A developmental product-research approach guided formulation, and a Randomized Complete Block Design (RCBD) with three replications guided evaluation. Ten household panelists rated flammability and burning time using a five-point scale. The researcher recorded mosquito knockdown observations at 2, 4, and 6 hours, and panelists verified the records using video recordings. Knockdown ratings were derived from the six-hour percentages. Thirty live *Anopheles* mosquitoes were exposed per treatment per replication, with observations at 2, 4, and 6 hours. After six hours, mosquitoes unresponsive to a tap test were recorded as dead and observed until the following day; no movement or recovery was observed. Death was not independently confirmed through a separate laboratory test. Weighted means summarized ratings, and RCBD analysis of variance tested treatment differences at the 0.05 significance level.

Results: All formulations had a mean flammability rating of 3.00. The transfluthrin control had the highest burning-time rating (5.00), followed by citronella roots (4.00), while leaves and pseudostem both rated 3.33. For knockdown response, the control rated 5.00, leaves and roots rated 3.00, and pseudostem rated 2.33. At two hours, mean knockdown responses were 85.56% for the control, 7.78% for leaves, 8.89% for pseudostem, and 4.44% for roots. Treatment differences were significant, $F(3, 6) = 20.83, p = .0014$. Final recorded mortality was 100.00% for the control, 52.22% for leaves, 35.56% for pseudostem, and 50.00% for roots.

Conclusion: Mosquito coils can be formulated using citronella plant parts and charcoal-based materials. The transfluthrin control showed the highest observed knockdown response and final recorded mortality; the citronella formulations showed lower responses under the study conditions. Further optimization, controlled mosquito trials, and emission testing are recommended.

Keywords: *Citronella grass, bio-based mosquito coil, mosquito knockdown response, Anopheles mosquitoes, product development*

INTRODUCTION

Mosquitoes affect human populations and transmit pathogens that cause dengue, malaria, yellow fever, and Japanese encephalitis. One report estimated that mosquito-borne diseases sickened over 700 million people and caused more than one million deaths annually (Nasci et al., 2008). These diseases disproportionately affect tropical and subtropical regions, where household protection complements community vector-control programs (Corzo-Gómez et al., 2024).

Mosquito coils are an inexpensive household protection method in many developing communities. Along with vaporizer mats and other emanators, they release airborne active ingredients that can cause mosquito mortality, deterrence, or repellency and reduce biting (Begum et al., 2026). Synthetic coils remain widely used, despite concerns about cost, insecticide resistance, and indoor air quality.

Indoor use of synthetic coils raises health and environmental concerns. Their combustion can release fine particulate matter (PM_{2.5}), polycyclic aromatic hydrocarbons (PAHs), aldehydes, and other pollutants; predicted indoor concentrations may exceed health-based air-quality guidelines (Sharma et al., 2024). These risks must be weighed against their protective benefits (Sharma et al., 2024). This has increased interest in botanical repellents. Plant essential oils are potential alternatives to synthetic repellents such as *DEET* (N,N-diethyl-3-methylbenzamide) (Mishra et al., 2023). A citronella-oil blend with insect-derived oils provided complete protection for 3.50 hours against *Anopheles gambiae* and 2.56 hours against *Aedes aegypti* in one study (Ochola et al., 2026). Botanical actives still require systematic evaluation rather than assumptions of universal safety (Noguera-Gahona et al., 2025). Citronella grass (*Cymbopogon nardus*) is a source of aromatic essential oil with mosquito-repellent properties (Kamal et al., 2024). Herbal formulations have also used cardamom seed (Das et al., 2021) and neem and *Flemingia strobilifera* leaves (Iraqi et al., 2022). Because citronella actives are volatile, their protection time is limited; fixatives and matrix systems may prolong their effect (Iovinella et al., 2022). Incorporating citronella into a controlled-burning matrix therefore warrants investigation.

Synthetic coils remain an accessible household mosquito-control product in the Philippines. Citronella grass (*Cymbopogon nardus*) is grown for essential oil and other value-added products (Balaguer, 2024). Balaguer (2023) identified spent citronella leaves remaining after essential-oil extraction as a potential material for product diversification. In the present study, air-dried citronella leaves, pseudostem, and roots were evaluated for mosquito-coil production. Because citronella is locally available in Aklan, its use in bio-based household pest-control products merits study. However, comparative performance data for coils made from different citronella plant parts and charcoal fillers are limited. Neem and coconut shell charcoal powders were included as formulation components based on reported combustion characteristics. Emissions, including PM_{2.5} and PAHs, were not measured. Comparing leaves, pseudostem, and roots within one species may help identify plant parts for further formulation development.

This study investigates locally available citronella biomass for mosquito-coil development. It compares formulations using leaves, pseudostem, and roots in terms of flammability, burning time, knockdown response, and recorded mortality, providing a basis for future optimization and controlled testing.

Review of Related Literature

Development of Mosquito Coils

Mosquito coils are smoldering devices that release smoke and vaporized active ingredients over several hours. They typically contain an active ingredient, fillers to support combustion, a binder, and additives (Modibbo & Kabir, 2026). Widely used indoors and outdoors, synthetic coils raise concerns about cost, resistance, and indoor air quality. Laboratory studies of plant-based coils report repellency, knockdown, and mortality effects, while noting the need for standardized methods and adequate replication (Begum et al., 2026).

Plant-Based Materials for Mosquito Coils

Plants have long been used as mosquito fumigants, especially in rural tropical communities where commercial products may be scarce or costly (Mishra et al., 2023). A systematic review identified citronella, pine, peppermint, and other oils among effective botanical repellents against *Anopheles* species (Tilekar et al., 2024). Herbal coils have been formulated from neem and *Flemingia strobilifera* leaves (Iraqi et al., 2022) and from cardamom seeds using a natural binder (Das et al., 2021). Recent studies support the technical feasibility of developing plant-based repellents (Das et al., 2021; Modibbo & Kabir, 2026).

Citronella as a Repellent Active

Citronella grass (*Cymbopogon nardus*) contains essential oils rich in citronellal, citronellol, and geraniol, which have mosquito-repellent activity (Mishra et al., 2023). Burning the plant releases volatile compounds (Uopasai et al., 2024). Citronella oil often provides short protection because its active components are highly volatile, although modified citronellal derivatives have shown longer protection than *DEET* at equivalent concentrations (Iovinella et al., 2022). These findings support incorporating citronella into a slow-burning coil matrix to prolong volatile release.

Charcoal Base Materials and Emission Reduction

Base materials affect mosquito-coil combustion and emissions. Burning coils can generate submicron particles and gaseous pollutants, and smoke exposure has been associated with acute and chronic health risks (Sharma et al., 2024). Because charcoal and raw biomass can differ in combustion characteristics, this study used neem and coconut shell charcoal powders as base materials.

Flammability and Burning Time

Flammability and burning time affect coil usability, active-material release, and performance consistency. These characteristics depend on formulation, binder distribution, density, moisture, and active-material concentration. Studies reporting several-hour burning times for plant-based coils support evaluating these properties during product development.

Repellency and Mortality Mechanisms

Mosquito coils may kill or knock down mosquitoes through insecticides or repel them through aromatic substances such as citronella (Begum et al., 2026). Burning plant materials releases volatile compounds, and studies have reported knockdown effects from plant-based coils (Begum et al., 2026). However, one laboratory evaluation found 93.3% mortality from a synthetic coil and substantially lower mortality from plant-based formulations, indicating that botanical coils may not provide equivalent lethal effects (Begum et al., 2026).

The literature supports the potential of botanical repellents, especially citronella, and shows that base materials, binders, combustion, and active ingredients affect coil performance. However, few studies compare different parts of the same plant in a standardized coil formulation. Evidence comparing the flammability, burning behavior, repellency, and knockdown response of citronella leaves, pseudostem, and roots remains limited. This study addresses that gap by developing and evaluating these formulations under a controlled design.

Synthesis and Research Gap

The literature indicates that citronella and other botanical materials may be useful in mosquito-control products and that base materials affect combustion. However, comparative data for coils made from different parts of the same plant remain limited. This study compared citronella leaf, pseudostem, and root coils with a synthetic control for flammability, burning time, knockdown response, and recorded *Anopheles* mortality using an RCBD with three replications.

Conceptual Framework

The study used an Input-Process-Output (IPO) product-development framework. Inputs were citronella leaves, pseudostem, and roots; neem and coconut shell charcoal powders; citronella-infused cooking oil; and cassava starch binder. Processing included harvesting, drying, pulverizing, weighing, mixing, preparing the paste and oil, molding, and baking. Outputs were flammability, burning time, mosquito knockdown response, and recorded *Anopheles* mortality.

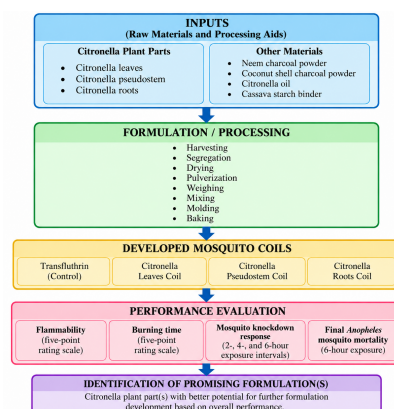
An RCBD with three replications was used to control variation among experimental blocks and evaluate the formulations.

Household panelists rated flammability and burning time using a five-point scale. The researcher recorded mosquito knockdown observations at 2-, 4-, and 6-hour intervals, and panelists verified the records using video recordings. Knockdown ratings were derived from the six-hour percentages.

For statistical analysis, analysis of variance (ANOVA) was used to determine whether significant differences existed among the treatment formulations. The conceptual framework of the study is presented in Figure 1.

Figure 1

Conceptual framework of the study (Input–Process–Output model)



Scope and Limitations

The project began in 2020; data gathering and evaluation by ten household panelists took place on April 11, 2021, in Barangay Laguianbanua West, Numancia, Aklan, Philippines. The study compared a transfluthrin control with citronella leaf, pseudostem, and root coils for flammability, burning time, knockdown response, and recorded *Anopheles* mortality.

The RCBD included three replications, with 30 mosquitoes per treatment per replication (360 exposures in total).

Limitations included field-collected rather than laboratory-cultured mosquitoes, few panelists and replications, and possible observer-rating variability. Emissions, including PM_{2.5} and PAHs, were not measured. Mortality was recorded after a tap test and observation for movement or recovery; it was not independently confirmed by a separate laboratory test. Results should be interpreted accordingly.

Statement of the Problem

Synthetic coils remain widely used, but concerns about coil smoke and pollutants have increased interest in botanical alternatives (Sharma et al., 2024). Although citronella is recognized for mosquito-repellent properties, evidence comparing coils made from different parts of *Cymbopogon nardus* remains limited (Sodangi et al., 2023; Balaguer, 2023).

Comparative data for citronella leaves, pseudostem, and roots are limited for flammability, burning time, knockdown response, and mortality. This limits the evidence available to households and developers considering locally available botanical materials.

This study developed and compared citronella leaf, pseudostem, and root coils under controlled experimental conditions.

Research Objectives

General Objective

To develop and evaluate mosquito coils formulated from different plant parts of citronella grass (*Cymbopogon nardus*) in terms of their functional performance and mosquito-control effects.

Specific Objectives

Specifically, the study sought:

1. To determine the functional performance of the developed mosquito coils in terms of:
 - o flammability;
 - o burning time; and
 - o mosquito knockdown response;
2. To determine the observed knockdown response of *Anopheles* mosquitoes at 2-, 4-, and 6-hour exposure intervals and the final recorded mortality following the exposure and subsequent observation period; and
3. To determine whether a statistically significant difference exists among the mosquito-coil formulations in terms of *Anopheles* mosquito knockdown response at the two-hour exposure interval.

Research Questions

The study sought to answer the following questions:

1. What is the functional performance of the developed mosquito coils in terms of flammability, burning time, and mosquito knockdown response?
2. What are the observed knockdown responses of *Anopheles* mosquitoes at 2-, 4-, and 6-hour exposure intervals, and the final recorded mortality for each mosquito-coil formulation following the exposure and subsequent observation period?
3. Is there a statistically significant difference among the mosquito-coil formulations in terms of *Anopheles* mosquito knockdown response at the two-hour exposure interval?

Hypothesis

H₀: There is no statistically significant difference in *Anopheles* mosquito knockdown response among the mosquito-coil formulations at the two-hour exposure interval.

METHODOLOGY

Research Design

The study used a developmental product-research approach to formulate bio-based coils and an RCBD to evaluate four formulations. The development approach guided formulation using different citronella plant parts; the RCBD organized evaluation across three replications.

Locale and Panelists

The study was conducted in Barangay Laguinbanua West, Numancia, Aklan, Philippines. Ten adult panelists with mosquito problems who used transfluthrin coils participated: five housewives, two college students, and three private employees. They were screened and physically assessed for asthma and other respiratory ailments before exposure to coil smoke.

Materials and Formulation

Four treatments were prepared: Treatment 1 (T1), the transfluthrin control; Treatment 2 (T2), citronella leaves; Treatment 3 (T3), citronella pseudostem; and Treatment 4 (T4), citronella roots. The botanical treatments consisted of a dry plant-and-charcoal base containing 50% citronella plant material, 25% neem charcoal powder, and 25% coconut shell charcoal powder by mass. Citronella-infused cooking oil and cassava starch paste were added separately. The formulation matrix is presented in Table 1.

Table 1

Formulation matrix of the mosquito-coil treatments

Ingredient	T1 (control)	T2 (leaves)	T3 (pseudostem)	T4 (roots)
Transfluthrin	Present	-	-	-
Citronella leaves (g)	-	29.60	-	-
Citronella pseudostem (g)	-	-	29.60	-
Citronella roots (g)	-	-	-	29.60
Neem charcoal powder (g)	-	14.80	14.80	14.80
Coconut shell charcoal powder (g)	-	14.80	14.80	14.80
Citronella-infused oil (mL)	-	4.93	4.93	4.93
Cassava starch paste (mL)	-	14.80	14.80	14.80

Note. T1 = transfluthrin control; T2 = citronella leaves; T3 = citronella pseudostem; T4 = citronella roots.

Citronella leaves, pseudostem, and roots were air-dried for at least one week away from direct sunlight and strong airflow, then cut and ground to a fine, meal-like texture similar to finely ground livestock feed; particle size was not measured. Cassava starch paste was prepared by cooking 29.60 g of dry cassava starch in 150 mL of water. The prepared paste was measured by volume, and 14.80 mL was added to each botanical formulation. Citronella-infused cooking oil was prepared by double-boiling 75 g fresh citronella strips in 500 mL cooking oil for about 30 minutes. Neem and coconut-shell charcoal were pulverized and sifted. Weighed ingredients were mixed and molded into coils patterned after commercial coils; final coil mass was not recorded. Coils were baked at 100 °C for 60 minutes. Tools included a coffee grinder, kitchen knife, cutting board, measuring cups and spoons, mixing bowl, sifter, pan, spoon, mortar and pestle, scissors, oven, and stopwatch.

Experimental Design

The experiment used an RCBD with four treatments and three replications. Each block contained all four treatments, assigned by drawing lots. Treatments were tested separately to reduce possible interference from smoke exposure. The order was T1, T2, T3, T4 in Replication 1; T1, T2, T4, T3 in Replication 2; and T3, T2, T1, T4 in Replication 3. Each treatment cage held 30 live *Anopheles* mosquitoes, giving 120 per replication and 360 overall. The same mosquitoes were observed at 2, 4, and 6 hours; each replication was one complete experimental run and served as a block.

Data Gathering Instrument

An evaluation score sheet using a five-point scale was used by the panelists to rate flammability and burning time. Flammability ratings (5 = extremely flammable; 1 = non-flammable) were based on ignition time, while

burning-time ratings (5 = extremely lasting; 1 = non-lasting) were based on burn duration. For mosquito knockdown response, the researcher recorded the number of mosquitoes no longer moving at the 2-, 4-, and 6-hour observation intervals. The panelists verified the observations using video recordings. The knockdown ratings reported in Table 2 were derived for each replication from the six-hour knockdown percentage using the percentage ranges specified in the table note.

Mosquito counts were used for the separate final mortality assessment. After six hours, mosquitoes unresponsive to a tap test were recorded as dead and observed until the following day for movement or recovery. Mortality percentage was calculated as recorded dead mosquitoes divided by the number exposed, multiplied by 100. Video recordings documented activity, and panelists verified the recorded data.

The research adviser, research expert, specialization expert, statistics expert, and English language expert validated the score sheet. Their recommendations were incorporated into the final instrument.

Data Collection Procedure

Data were gathered in three stages: pre-experimental, experimental, and post-experimental stages.

Pre-experimental Stage. Before testing, ingredients, tools, and equipment were checked for cleanliness, dryness, and condition. Citronella leaves, pseudostem, and roots were harvested, separated, air-dried away from direct sunlight, cut, and pulverized. Neem and coconut-shell charcoal powders, citronella-infused cooking oil, and cassava starch binder were prepared. Ingredients were weighed, mixed, molded into coils, and baked according to the formulation procedure.

Experimental Stage. The four treatments were tested in three replications, separately to reduce interference from smoke; tests occurred at different times on the same or different days. For each treatment and replication, 30 live *Anopheles* mosquitoes were placed in a cage, totaling 120 per replication and 360 overall. Panelists rated flammability by ignition time and burning time from ignition until the coil stopped burning, using the five-point scale.

The same mosquitoes in each cage were observed at 2, 4, and 6 hours, and those no longer moving were recorded as showing knockdown. Video documented activity. After six hours, mosquitoes unresponsive to a tap test were recorded as dead and observed in their cages until the following day for movement or recovery. The researcher recorded the observations, panelists verified the records, and mortality percentages used 30 exposed mosquitoes per treatment per replication as the denominator. Results were recorded separately by treatment and replication.

Post-experimental Stage. After testing, score sheets, observations, and video recordings were checked for consistency. Data were organized, tallied, encoded, and verified by panelists before treatment- and replication-level summaries and statistical analysis.

Data Analysis

Score-sheet data were tabulated by treatment and replication. Weighted means summarized panelists' ratings of flammability and burning time. Knockdown ratings for each replication were derived from the six-hour knockdown percentages using the percentage ranges in Table 2. The treatment-level knockdown rating was the mean of the three replication ratings. Observations were verified by panelists and supported by video. Mortality percentage was calculated as recorded dead mosquitoes divided by 30 exposed per treatment per replication, multiplied by 100; results were interpreted according to the observation procedure.

RCBD analysis of variance (ANOVA) tested differences among the four formulations in two-hour knockdown response at $\alpha = 0.05$, considering treatment and block/replication effects. The null hypothesis was rejected when $p < .05$ and not rejected when $p \geq .05$. Calculations used Microsoft Excel 2016.

Ethical Considerations

The project began in 2020, and data gathering with ten household panelists occurred on April 11, 2021. The Barangay Captain granted permission to conduct the study in Barangay Laguinbanua West, Numancia, Aklan. All panelists gave written informed consent after being informed of the study, possible coil-smoke exposure, and their right to withdraw.

Panelists were screened for respiratory conditions, and coil-smoke testing took place in a well-ventilated area. Precautions were used to handle and contain live mosquitoes. COVID-19 measures in place in 2021—including distancing, masks, face shields, sanitation, and temperature checks—were followed.

The thesis adviser's "Noted" signature acknowledges the research document and is not institutional ethics-board approval. No separate ethics-board approval record was available. Accordingly, this manuscript reports only the documented permissions, informed consent, and safety precautions and does not claim formal ethics-board approval.

RESULTS AND DISCUSSION

Performance Mean Scores of the Formulations

Table 2 summarizes the formulations' mean ratings for flammability, burning time, and knockdown response. All four received a flammability rating of 3.00 (moderately flammable).

Table 2

Mean performance ratings of the mosquito coil formulations across evaluated parameters

Formulation	Flammability	Burning time	Knockdown Response
T1 Transfluthrin (control)	3.00	5.00	5.00
T2 Citronella leaves	3.00	3.33	3.00
T3 Citronella pseudostem	3.00	3.33	2.33
T4 Citronella roots	3.00	4.00	3.00

Note. Knockdown ratings were assigned to each replication using the six-hour knockdown percentage: 5 = 81–100%, 4 = 61–80%, 3 = 41–60%, 2 = 21–40%, and 1 = 0–20%. The reported treatment rating is the mean of the three replication ratings. Flammability and burning-time ratings used their respective scales.

Flammability

Ignition times were 9 seconds for the control, leaves, and pseudostem coils and 7 seconds for roots, the fastest. Despite this difference, all formulations received the same flammability rating (3.00, moderately flammable) on the five-point scale.

Burning Time

The control burned for 8:20:30, 8:19:27, and 8:13:41 across the three replications and had the highest mean rating (5.00, extremely lasting). The roots coil burned for 6:40:26, 6:44:35, and 7:08:51 and rated 4.00 (very much lasting). The leaves coil burned for 6:03:07, 6:09:04, and 3:40:28; the pseudostem coil for 4:30:24, 4:11:15, and 6:04:49. Both rated 3.33 (moderately lasting). Earlier research reported approximately six to seven hours for some plant-based coils (Modibbo & Kabir, 2026). Mean actual burning durations were 8:17:53 for the control, 5:17:33 for leaves, 4:55:29 for pseudostem, and 6:51:17 for roots.

Observed Mosquito Knockdown Response

Table 3 shows observed *Anopheles* knockdown percentages at 2, 4, and 6 hours.

Table 3

Mosquito knockdown response (%) of Anopheles mosquitoes at 2-, 4-, and 6-hour exposure intervals

Formulation	Replication	2 hours	4 hours	6 hours
T1 Transfluthrin (control)	R1	100.00	100.00	100.00
	R2	56.67	100.00	100.00
	R3	100.00	100.00	100.00
T2 Citronella leaves	R1	20.00	33.33	56.67
	R2	0.00	23.33	46.67
	R3	3.33	53.33	53.33
T3 Citronella pseudostem	R1	0.00	6.67	23.33
	R2	3.33	13.33	13.33
	R3	23.33	70.00	70.00
T4 Citronella roots	R1	0.00	3.33	23.33
	R2	10.00	33.33	53.33
	R3	3.33	26.67	73.33

Note. Percentages show mosquitoes observed knocked down at 2, 4, and 6 hours for each treatment and replication, using 30 exposed mosquitoes as the denominator. These interval observations are separate from the final assessment after six hours. The six-hour counts correspond to those recorded as dead after the tap test and subsequent observation.

At two hours, mean knockdown was 85.56% for the control, 7.78% for leaves, 8.89% for pseudostem, and 4.44% for roots. These descriptive results show differences in observed response. Knockdown is not the same as confirmed mortality; two-hour observations represent knockdown, not confirmed death.

Plant materials can release volatile compounds associated with mosquito-control activity (Modibbo & Kabir, 2026; Das et al., 2021). However, this study did not chemically analyze the formulations, so differences cannot be

attributed to active-compound concentrations. The results describe observed knockdown and are not from a standardized mosquito-repellency assay.

Statistical Analysis of Knockdown Response

Table 4 presents the RCBD analysis of two-hour *Anopheles* knockdown response.

Table 4

Analysis of variance for Anopheles mosquito knockdown response at the two-hour exposure interval

Source	df	SS	MS	F	p
Treatments	3	13,904.61	4,634.87	20.83	.0014
Blocks/Replications	2	516.55	258.28	1.16	.3749
Error	6	1,335.09	222.51	—	—
Total	11	15,756.24	—	—	—

Note. $\alpha = .05$.

RCBD analysis showed a significant difference among the four formulations in observed two-hour knockdown response, $F(3, 6) = 20.83$, $p = .0014$. Because $p < .05$, the null hypothesis was rejected.

Final Mortality Assessment of Anopheles Mosquitoes

After six hours, a tap test was performed. Mosquitoes that did not move or fly in response were recorded as dead, then kept in their cages until the following day; no movement or recovery was observed. Final mortality was calculated from recorded deaths out of 30 mosquitoes per treatment per replication. Table 5 presents the counts and percentages.

Table 5

Final mortality counts and percentages of Anopheles mosquitoes by treatment

Formulation	R1 (n)	R2 (n)	R3 (n)	Total dead (n/90)	Mortality (%)
T1 Transfluthrin (control)	30	30	30	90/90	100.00
T2 Citronella leaves	17	14	16	47/90	52.22
T3 Citronella pseudostem	7	4	21	32/90	35.56
T4 Citronella roots	7	16	22	45/90	50.00

Note. Each treatment included 30 mosquitoes per replication, for a total of 90 mosquitoes per treatment. Mortality (%) = (total number recorded as dead ÷ total number exposed) × 100.

Recorded final mortality was highest for the control (100.00%), followed by leaves (52.22%), roots (50.00%), and pseudostem (35.56%). These are results of the study's tap-test and follow-up observation procedure; death was not independently confirmed by a separate laboratory test.

Industrial Engineering Implications

The study demonstrated practical preparation of bio-based coils from local citronella biomass and charcoal-based materials. Processing involved drying, cutting, pulverizing, sifting, mixing, molding, and baking. These steps provide a basis for further work on process standardization, material use, production efficiency, and quality control.

Using citronella leaves, pseudostem, and roots may support value-added plant use. However, PM_{2.5} and PAH emissions were not measured, so no conclusion about emission reduction or cleaner combustion is supported. The observed results also do not establish efficacy equivalent to the synthetic control.

Further manufacturing studies could assess production efficiency, material use, productivity, cost, quality assurance, standardization, and pilot-scale production. They could also optimize particle size, moisture, formulation proportions, binder concentration, molding, and drying or baking conditions. Local citronella biomass may offer value-added and small-scale livelihood opportunities, subject to further evaluation.

Conclusion

All formulations received a mean flammability rating of 3.00 (moderately flammable). For burning time, the control rated 5.00 (extremely lasting), roots 4.00 (very much lasting), and leaves and pseudostem 3.33 each (moderately lasting). For knockdown response, the control rated 5.00, leaves and roots 3.00 each, and pseudostem 2.33.

At two hours, mean knockdown response was 85.56% for the control, 7.78% for leaves, 8.89% for pseudostem, and 4.44% for roots. The RCBD showed significant treatment differences, $F(3, 6) = 20.83$, $p = .0014$, indicating different observed knockdown responses under the study conditions.

After six-hour exposure, a tap test, and follow-up observation until the next day, recorded mortality was 100.00% for the control, 52.22% for leaves, 50.00% for roots, and 35.56% for pseudostem. These are recorded outcomes, not independently confirmed mortality. The two-hour data represent knockdown response. Further trials should validate performance and independently confirm mortality.

Recommendations

1. Optimize the botanical coils by testing binder ratio, particle size, moisture, ingredient proportions, and drying or baking conditions to improve burning characteristics and consistency.
2. Conduct more replications and, where feasible, use laboratory-cultured mosquitoes. Apply a defined knockdown procedure and an independent method to confirm mortality.
3. Assess scale-up potential through studies of production efficiency, material use, cost-effectiveness, quality control, and dimensional consistency before larger-scale production.
4. Measure emissions, especially $PM_{2.5}$ and PAHs, to characterize the coils and assess potential environmental or health effects.
5. Test citronella and other locally available botanicals, such as lemongrass, basil, kakawate, and oregano, through appropriate comparative experiments.
6. Evaluate additional quality variables, including burn rate, smoke, coil dimensions, final mass, and storage stability, to support product standardization.

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