Original Article

Laboratory Evaluation of a Non-Insecticide Multimodal Trap Using Carbon Dioxide, Lactic Acid, Ultraviolet-A Light and Sound Frequency for *Aedes aegypti* Control

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Abstract

Background: Dengue remains an important public health problem in tropical and subtropical settings. *Aedes aegypti* is a principal dengue vector and is highly adapted to domestic environments. Because repeated chemical-based control may contribute to insecticide resistance and environmental exposure, practical non-insecticide tools are needed. This study evaluated a non-insecticide multimodal trap integrating carbon dioxide, lactic acid, ultraviolet-A light and sound frequency for *Ae. aegypti* control.

Methods: This quasi-experimental study evaluated a laboratory prototype multimodal trap. A total of 2,850 female *Ae. aegypti* mosquitoes were used for multimodal combination testing and commercial-trap comparison after preliminary attractant optimization. The colony was obtained from the Parasitology Laboratory, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia. Non-blood-fed females aged 3–5 days were used. Each treatment included three replications of 50 mosquitoes. Outcomes were analyzed using the General Linear Model and repeated ANOVA.

Results: Lactic acid was the most effective single attractant (78.66%). The four-mode combination produced the highest mean effectiveness (91.33%), with a maximum observed value of 98%. In the enclosed-room test, the multimodal trap performed significantly better than the Mosquito Killer BG-360 and the suction-only negative control, but not significantly better than the Photocatalyst Mosquito and Fly Trap.

Conclusion: The non-insecticide multimodal trap showed promising laboratory effectiveness for capturing or electrocuting *Ae. aegypti*. Semi-field and field trials are needed to assess operational effectiveness, feasibility, electrical safety and durability.

Keywords: Dengue prevention; Host-seeking behavior; Integrated vector management; Non-chemical intervention; Suction device

Introduction

Dengue hemorrhagic fever remains a serious public health problem in many tropical and subtropical regions, including Indonesia. Dengue transmission is influenced by environmental conditions, population density, human mobility and the presence of competent mosquito vectors (1). *Aedes aegypti* is recognized by the World Health Organization as the principal vector of dengue viruses in urban and peri-urban settings (2). Its strong adaptation to human dwellings and frequent human-biting behavior contribute to its important role in dengue transmission. The uncontrolled presence of adult mosquitoes and breeding sites can increase the risk of dengue transmission in the community. Therefore, vector population control remains an important strategy in dengue prevention because transmission can be reduced when adult mosquito density and breeding habitats are consistently suppressed (3, 4).

Efforts to control dengue vectors have been carried out through environmental, physical-mechanical, biological and chemical approaches. Environmental control includes mosquito breeding-site control and the 3M Plus movement, such as draining water containers, covering water-storage containers, burying or recycling unused items, and implementing additional measures to prevent mosquito breeding. Physical-mechanical approaches include mosquito nets, wire screens, electric rackets and mosquito traps. Biological control may involve larval predators, such as larva-eating fish and microbial larvicides, including Bacillus thuringiensis israelensis. These approaches form part of integrated vector management, which aims to suppress mosquito populations through a combination of safe and sustainable strategies (5–8).

Environmental and biological control remain important components of integrated vector management; however, their effectiveness may depend on sustained community participation, ecological suitability, routine monitoring and adequate implementation coverage. Chemical control can rapidly reduce adult mosquito populations but may be limited by insecticide resistance and concerns related to repeated environmental exposure. Physical methods, including traps and portable sound-based or ultrasonic approaches, may provide complementary options, although their effectiveness depends on device design, attractant composition, operational setting and mosquito species. Sound-based or ultrasonic devices may offer practical advantages because they can be developed as safe, portable and user-friendly tools for household mosquito control; however, their effectiveness should be evaluated according to the mosquito species, frequency range, exposure setting, and device configuration.

Although these vector control approaches are widely applied, their implementation still faces several operational challenges. Source reduction and community-based mosquito control depend heavily on sustained household participation, regular monitoring and environmental sanitation. Their effectiveness may decline when community involvement is inconsistent or when domestic environments contain numerous artificial containers suitable for mosquito breeding. These conditions indicate the need for additional tools that can complement existing vector control strategies and support adult mosquito reduction in domestic and peri-domestic settings (4, 8).

The use of insecticides remains one of the most widely applied methods to suppress adult mosquito populations, particularly during dengue outbreaks. Fogging can rapidly reduce adult mosquito populations, but its effect is temporary without continuous source reduction (9). However, repeated and uncontrolled insecticide use may lead to reduced susceptibility of *Ae. aegypti* to certain active ingredients. Several studies in Indonesia have reported resistance or reduced susceptibility to pyrethroid and organophosphate insecticides. Therefore, chemical-based control should not be used as the sole strategy because it may reduce the long-term effectiveness of dengue vector-control programs (10–12).

Innovation in mosquito traps has been driven by the use of mosquito host-seeking behavior. Female mosquitoes recognize hosts through a combination of olfactory, visual, thermal and acoustic stimuli. Carbon dioxide not only functions as a chemical signal but can also strengthen host-seeking responses related to orientation toward heat or host body temperature (13). Carbon dioxide and lactic acid act as chemical cues, whereas ultraviolet-A light and sound frequency may serve as physical stimuli that influence mosquito flight orientation. Lactic acid is known to increase mosquito attraction because it resembles a component of human body odor recognized by dengue vectors (14–18).

A multimodal approach may improve trap effectiveness because several mosquito sensory systems are stimulated simultaneously. Traps using only one attractant or limited stimuli may have lower attractiveness because they activate only one mosquito response pathway. Local studies have shown that different attractants can produce variation in the number of mosquitoes captured, whereas traps based on limited physical stimuli, such as ultraviolet light and fans, do not always demonstrate strong effectiveness. Therefore, combining chemical attractants and physical stimuli may strengthen mosquito orientation toward traps (19, 20).

The combination of carbon dioxide, lactic acid, ultraviolet-A light and sound frequency may provide more complex olfactory, visual and acoustic stimulation. Previous studies have indicated that combined stimuli can increase mosquito landing and host-seeking responses compared with a single attractant. Recent laboratory evaluation of synthetic attractants has also supported the relevance of attractant-based screening for mosquito-trap development. This provides a basis for developing multimodal traps as a complementary approach for adult mosquito control (21–23).

Based on this background, this study developed and tested a non-insecticide multimodal trap integrating carbon dioxide, lactic acid, ultraviolet-A light and sound frequency for *Ae. aegypti* control. This study aimed to determine the effectiveness of single attractants and multimodal attractant combinations based on the number of captured or electrocuted mosquitoes and to compare the performance of the multimodal trap with commercial traps. The findings are expected to contribute to the development of a practical and environmentally safer tool for adult mosquito control within dengue vector-management programs.

Materials and Methods

Study design

The study was conducted from 31 May to 17 December 2019 at the Production House Laboratory and the Parasitology Laboratory, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia. Prototype construction and technical testing were conducted at the Production House Laboratory, while mosquito rearing and functional evaluation of the trap were conducted at the Parasitology Laboratory. Glass-chamber and enclosed-room experiments were conducted under controlled laboratory conditions.

Mosquito samples

A total of 2,850 female *Ae. aegypti* mosquitoes were used for multimodal combination testing and comparison with commercial mosquito traps. Preliminary chemical attractant optimization was conducted separately before the multimodal experiments. The mosquito colony was obtained from the Parasitology Laboratory, Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia. The mosquitoes were reared under standard insectary conditions until the adult stage. Female mosquitoes aged 3–5 days were selected because this age range represents an active host-seeking stage suitable for evaluating attraction-based trapping responses. Before testing, the mosquitoes were maintained on a 10% sucrose solution. Mosquitoes were maintained under controlled insectary conditions at 27–28 °C and 80–82% relative humidity. Only active, morphologically normal, non-blood-fed female mosquitoes were included in the experiments. Female mosquitoes were selected because they are the blood-seeking sex responsible for dengue virus transmission and are therefore the biologically relevant target for host-attractant-based trapping strategies.

Trap prototype

The trap prototype consisted of a liquid carbon dioxide delivery system, a lactic acid attractant container, an ultraviolet-A lamp, a sound device operating at 350–400 Hz, a suction fan and an electric-shock system. The prototype was designed to integrate chemical, visual, acoustic and mechanical stimuli to attract and capture or electrocute *Ae. aegypti* mosquitoes. Technical testing was conducted to determine the working configuration of each component before functional evaluation. Functional testing was then carried out in stages using single attractants, two-mode combinations, three-mode combinations and four-mode combinations.

The sound frequency range of 350–400 Hz was selected during prototype optimization because this setting produced active mosquito movement around the trap during technical testing. This range was also consistent with previous reports indicating that mosquitoes can respond to acoustic stimuli within comparable frequency ranges. However, the selected frequency was not intended to represent an established optimal frequency for female *Ae. aegypti*. Further studies are needed to compare different frequency ranges and determine their specific effects on mosquito orientation and trap response.

The electric-shock system was tested using a Fluke 101 instrument. The measured output was 110.1 VDC with a current of 100 mA, and the electric-shock grid produced a voltage of approximately 540 V. The electric-shock component was enclosed within a protective housing to minimize accidental contact during laboratory operation. Electrical wiring and grid components were insulated, and the prototype was operated only under supervised laboratory conditions. The present study did not evaluate household electrical safety or user acceptability; therefore, further safety assessment is required before domestic deployment.

Carbon dioxide and lactic acid preparation

Carbon dioxide was generated from liquid CO_2 using a humidifier-based delivery system connected to the trap. The CO_2 output was assessed during technical testing using a Lutron Hot Wire Anemometer AM-4202 and a Lutron GCH-2018 CO_2 meter. The selected configuration produced a CO_2 output of approximately 103 mL/min and a flow rate above 100 mL/min was used as the operating condition for subsequent testing. During optimization, liquid CO_2 formulations of 1, 5, 10 and 15% were evaluated, and the 10% liquid CO_2 formulation produced the highest mosquito response. The percentage of liquid CO_2 formulation referred to the concentration setting of the liquid CO_2 source prepared for humidifier-based delivery, whereas the operating output was evaluated as CO_2 flow rate during technical testing.

Lactic acid was obtained as a commercially available laboratory-grade product and diluted with distilled water to prepare working concentrations of 1, 5, 10 and 15% before testing. The 10% lactic acid formulation produced the highest mosquito response and was selected for the subsequent multimodal combination test.

Experimental procedures

The experimental procedures consisted of technical prototype testing, chemical attractant optimization, multimodal combination testing and comparison with commercial mosquito traps. Each treatment was performed in three replications, with 50 female *Ae. aegypti* mosquitoes used in each replication. Three replications were used to provide repeated measurements for each treatment condition and to allow descriptive assessment of within-treatment variability. Female *Ae. aegypti* mosquitoes aged 3–5 days were non-blood-fed and had been maintained on a 10% sucrose solution before testing. The number of mosquitoes used for each treatment and control condition is presented in the corresponding tables. In each test, female *Ae. aegypti* mosquitoes were released into the testing chamber or enclosed room, and the trap was operated according to the assigned treatment condition. A total of 2,850 female *Ae. aegypti* mosquitoes were derived from 15 multimodal combination treatments and four commercial-trap comparison groups, with each treatment or comparison group tested in three replications of 50 mosquitoes. Preliminary chemical attractant optimization was conducted separately before these experiments.

The tested stimuli included carbon dioxide, lactic acid, ultraviolet-A light and sound frequency, either as single attractants or in multimodal combinations. The multimodal trap was compared with the Mosquito Killer BG-360, the Photocatalyst Mosquito and Fly Trap, and a suction-only negative control. The suction-only negative control consisted of the prototype operated without carbon dioxide, lactic acid, ultraviolet-A light, or sound-frequency stimulation, while only the suction fan remained active. Data were collected through direct observation at the 1st, 2nd and 24th hour after trap activation. At each observation time, the cumulative number of mosquitoes captured by the suction system or electrocuted by the electric-shock component was recorded for each replication. The same cohort of mosquitoes was observed sequentially at each observation time within the same experiment. Mosquitoes captured by the suction system were recorded as captured mosquitoes, whereas mosquitoes that were immobile and confirmed dead after exposure to the electric-shock component were recorded as electrocuted mosquitoes. Knockdown mosquitoes were recorded separately as temporarily immobilized mosquitoes and were not categorized as electrocuted unless they were confirmed dead.

In this study, trap effectiveness was defined as the proportion of mosquitoes captured by the suction system or electrocuted by the electric-shock component during the observation period. Temperature, humidity, the number of mosquitoes in each test, observation time and replication number were controlled to maintain comparability between treatments.

Statistical analysis

The data were analyzed descriptively and inferentially. Inferential analysis was performed using the General Linear Model and repeated ANOVA, followed by Bonferroni-adjusted post hoc pairwise comparisons to examine differences across observation times and treatments. Repeated ANOVA was used because the same cohort of mosquitoes was observed sequentially at the 1st, 2nd and 24th hour after trap activation. Statistical significance was determined based on the p-value obtained from the analysis.

Results

Technical performance of the prototype

The technical test showed that the main components of the trap functioned according to the intended design. The configuration that produced the best mosquito response consisted of a carbon dioxide flow rate above 100 mL/min, a 13-watt ultraviolet-A lamp, a sound frequency of 350–400 Hz, and a suction fan speed of 600 rpm. This configuration was used as the basis for testing attractant combinations because it induced more active mosquito behavior around the trap (Table 1).

The technical test results showed that each component of the multimodal trap was able to generate active mosquito responses around the trap area. The best configuration of each component became the basis for using the device in the attractant and multimodal combination tests. These findings indicate that the prototype had fulfilled its initial technical functions before further effectiveness evaluation against *Ae. aegypti* was conducted.

Chemical attractant optimization

Chemical attractant optimization showed that 10% lactic acid produced the highest number of captured or electrocuted mosquitoes, namely 40 mosquitoes or 80%. Carbon dioxide was generated from liquid CO_2 using a humidifier-based delivery system. The 10% liquid CO_2 formulation produced 39 captured or electrocuted mosquitoes, corresponding to 78% effectiveness. These results were used to select the attractant conditions for the multimodal combination test (Table 2).

The optimization results showed that the 10 % lactic acid formulation and the 10% liquid CO_2 formulation produced the highest responses in their respective tests. The lower response at the 15% formulation suggests that increasing the concentration does not necessarily increase mosquito attraction. Therefore, the 10 % lactic acid formulation and the 10% liquid CO_2 formulation were used in the subsequent multimodal combination test.

Effectiveness of multimodal combinations

Testing of various combinations showed that an increase in the number of attractant modes tended to increase the number of captured or electrocuted mosquitoes. The best single attractant was lactic acid, with a mean of 39.33 mosquitoes or 78.66%. The three-mode combination of ultraviolet-A light, sound frequency, and lactic acid reached 42 mosquitoes or 84%. The highest effectiveness was obtained from the four-mode combination of ultraviolet-A light, sound frequency, carbon dioxide and lactic acid, with a mean of 45.66 mosquitoes or 91.33% (Table 3).

The test results showed that the four-mode combination produced the highest effectiveness compared with single attractants as well as two- and three-mode combinations. The increase in the number of captured or electrocuted mosquitoes indicates a synergistic effect among chemical, visual and acoustic stimuli. This finding reinforces that the integration of carbon dioxide, lactic acid, ultraviolet-A light and sound frequency has the potential to improve the performance of multimodal traps against *Ae. aegypti*.

Not all multimodal combinations produced improved outcomes. In particular, the combination of sound frequency, carbon dioxide and lactic acid showed lower effectiveness than lactic acid alone. This finding suggests that the interaction among stimuli may depend on the specific combination, intensity, timing and spatial arrangement of attractants rather than simply on the number of modes included. The lower response in this three-mode combination may indicate that the absence of visual stimulation or possible interference among chemical and acoustic cues reduced mosquito orientation toward the trap.

Figure 1 illustrates the mean effectiveness of single, two-mode, three-mode and four-mode attractant combinations with standard deviation error bars. The four-mode combination showed the highest mean effectiveness, while the sound frequency + CO_2 + lactic acid combination showed the lowest effectiveness among the three-mode combinations. This visualization supports the tabulated findings and shows the variability across the three replications.

Comparison with commercial traps

In the enclosed-room test, the multimodal trap showed significantly higher performance than the Mosquito Killer BG-360 and the suction-only negative control (Table 4). Although the multimodal trap had a numerically higher mean number of captured or electrocuted mosquitoes than the Photocatalyst Mosquito and Fly Trap, the difference was not statistically significant ($p = 0.141$).

These findings indicate that the multimodal trap performed better than the Mosquito Killer BG-360 and the suction-only negative control under the tested laboratory conditions. The comparison with the Photocatalyst Mosquito and Fly Trap did not demonstrate a statistically significant difference; therefore, superiority over this comparator cannot be concluded.

Statistical analysis

The repeated ANOVA results showed a significant difference in the number of captured or electrocuted mosquitoes across the various attractant combinations ($p < 0.001$). Bonferroni-adjusted post hoc comparisons revealed significant differences in scores across the 1st, 2nd and 24th-hour observation time points. The number of captured or electrocuted mosquitoes increased with longer exposure duration, particularly in the four-mode combination (Table 5).

The statistical analysis further confirmed that variations in attractant combinations had a significant effect on the number of captured or electrocuted mosquitoes. Differences across observation times indicate that exposure duration also contributed to increased trap effectiveness. Therefore, both the attractant combination and exposure duration are important factors in the success of the multimodal trap against *Ae. Aegypti*.

Table 1. Technical performance of the non-insecticide multimodal trap prototype for attracting adult female *Aedes aegypti* under laboratory conditions in Yogyakarta, Indonesia, 2019

Component	Best Configuration	Mosquito Response
CO_2 flow	> 100 mL/min	Mosquitoes actively flew above the trap
UV-A lamp	13 W	Mosquitoes actively flew above the trap
Sound frequency	350–400 Hz	Mosquitoes actively flew above the trap
Suction fan	600 rpm	Mosquitoes were forcibly attracted while flying above the trap

Note: The prototype integrated liquid CO_2 delivery, a lactic acid attractant container, ultraviolet-A light, sound frequency, a suction fan and an electric-shock system. The table summarizes the component settings that produced active flight or attraction responses in adult female *Ae. aegypti* during preliminary technical testing conducted from 31 May to 17 December 2019 at the Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia

Table 2. Optimization of lactic acid concentration and liquid CO_2 formulation for capturing or electrocuting adult female *Aedes aegypti* in laboratory testing in Yogyakarta, Indonesia, 2019

Formulation (%)	Lactic acid: n (%)	Liquid CO_2 formulation: n (%)
1	13 (26)	7 (14)
5	19 (38)	21 (42)
10	40 (80)	39 (78)
15	33 (66)	8 (16)

Note: Values are presented as n (%), representing the number and percentage of 50 adult female *Ae. aegypti* mosquitoes captured or electrocuted under each formulation. Liquid CO_2 was delivered using a humidifier-based system connected to the trap. The selected operating condition produced a CO_2 output of approximately 103 mL/min, with a flow rate above 100 mL/min during technical testing. Experiments were conducted from 31 May to 17 December 2019 at the Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia

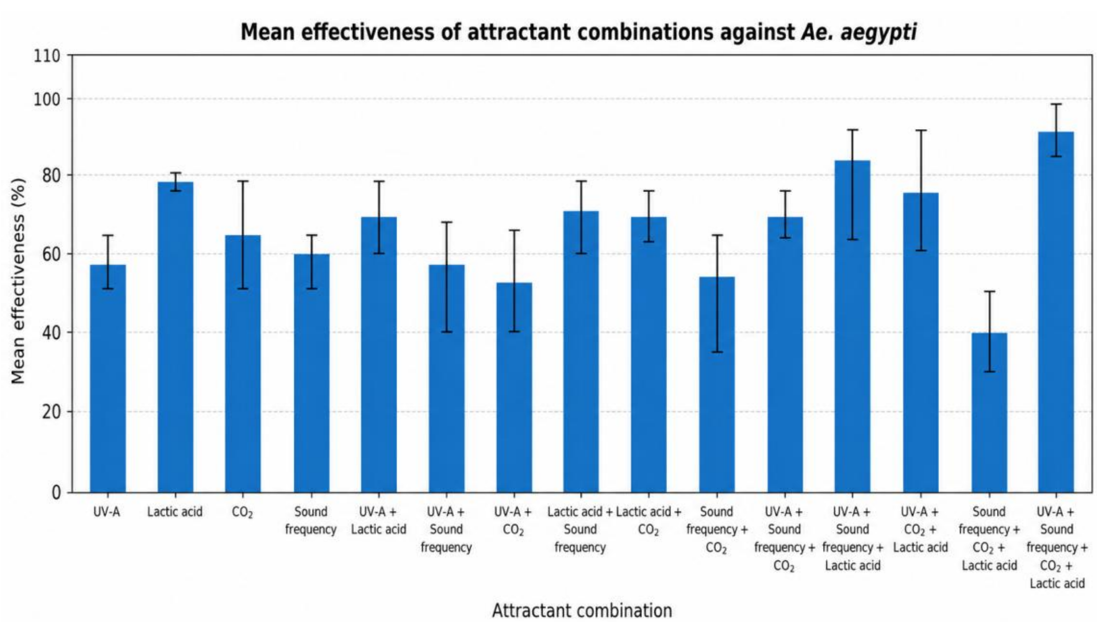

Fig. 1. Mean effectiveness of single, two-mode, three-mode and four-mode attractant combinations for capturing or electrocuting adult female *Aedes aegypti* in laboratory testing in Yogyakarta, Indonesia, 2019. Error bars represent standard deviations from three replications. Each replication used 50 female *Ae. aegypti* mosquitoes

Table 3. Mean effectiveness of single, two-mode, three-mode, and four-mode attractant combinations for capturing or electrocuting adult female *Aedes aegypti* in laboratory testing in Yogyakarta, Indonesia, 2019 (n= 50 mosquitoes per replication; three replications per treatment)

Attractant/Combination		Mean Number of Captured or Electrocuted Mosquitoes, Mean ± SD	Percentage (%)	Observed Range Across Replications (%)
Single attractants	UV-A	28.67 ± 3.05	57.34	52–64
	Lactic acid	39.33 ± 1.15	78.66	76–80
	CO_2	32.33 ± 6.11	64.66	54–78
	Sound frequency	30.00 ± 3.46	60.00	52–64
Two-mode combinations	UV-A + Lactic acid	34.67 ± 4.50	69.34	60–78
	UV-A + Sound frequency	28.67 ± 7.57	57.34	40–68
	UV-A + CO_2	26.33 ± 6.50	52.66	40–66
	Lactic acid + Sound frequency	35.33 ± 4.72	70.66	60–78
	Lactic acid + CO_2	34.67 ± 3.06	69.34	64–76
	Sound frequency + CO_2	27.00 ± 7.81	54.00	36–64
Three-mode combinations	UV-A + Sound frequency + CO_2	34.67 ± 2.89	69.34	66–76
	UV-A + Sound frequency + Lactic acid	42.00 ± 4.36	84.00	64–90
	UV-A + CO_2 + Lactic acid	37.66 ± 7.02	75.32	62–90
	Sound frequency + CO_2 + Lactic acid	19.67 ± 5.03	39.34	30–50
Four-mode combination	UV-A + Sound frequency + CO_2 + Lactic acid	45.66 ± 3.05	91.33	86–98

Note: Values are presented as means ± standard deviations of three replications. Each replication used 50 adult female *Ae. aegypti* mosquitoes. The observed range represents the minimum and maximum percentage of mosquitoes captured or electrocuted across the three replications. Experiments were conducted from 31 May to 17 December 2019 at the Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia.

Table 4. Comparison of the non-insecticide multimodal trap with commercial mosquito traps and a suction-only negative control for adult female *Aedes aegypti* in enclosed-room testing in Yogyakarta, Indonesia, 2019

Comparison	Multimodal Trap, Mean ± SD	Comparator Group, Mean ± SD	Mean difference	P value
Multimodal vs Mosquito Killer BG-360	34.66 ± 5.50	12.33 ± 3.05	22.33	< 0.001
Multimodal vs Photocatalyst Mosquito and Fly Trap	34.66 ± 5.50	21.66 ± 3.51	13.00	0.141
Multimodal vs Suction-only negative control	34.66 ± 5.50	1.33 ± 0.57	33.33	< 0.001

Note: Values are presented as means ± standard deviations of three replications. Each comparison group was tested with 50 adult female *Ae. aegypti* mosquitoes per replication. The suction-only negative control refers to the prototype operated without carbon dioxide, lactic acid, ultraviolet-A light, or sound-frequency stimulation, while only the suction fan remained active. Experiments were conducted from 31 May to 17 December 2019 at the Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia

Table 5. Repeated ANOVA and Bonferroni-adjusted post hoc analysis of captured or electrocuted adult female *Aedes aegypti* across attractant combinations and observation times in laboratory testing in Yogyakarta, Indonesia, 2019

Analysis	Comparison	P value	Interpretation
Repeated ANOVA	Various attractant combinations	< 0.001	There was a significant difference among treatments
Bonferroni post hoc	1st hour vs 2nd hour	0.013	Significantly different
Bonferroni post hoc	1st hour vs 24th hour	< 0.001	Significantly different
Bonferroni post hoc	2nd hour vs 24th hour	< 0.001	Significantly different

Discussion

The results of this study show that the non-insecticide multimodal trap achieved a high level of effectiveness in capturing or electrocuting *Ae. aegypti* mosquitoes. This finding is important for public health because *Ae. aegypti* is the primary vector of dengue transmission and has a high capacity to adapt to residential environments, particularly clean water containers commonly found around households. The relatively rapid life cycle of mosquitoes under optimal environmental conditions indicates that vector control must be carried out continuously and should not rely solely on a single intervention approach (2, 24).

The effectiveness of the multimodal trap in this study can be explained through the host-seeking behavior of female mosquitoes. *Aedes aegypti* does not respond to only one stimulus, but instead uses a combination of chemical, visual, thermal, humidity and acoustic cues to detect the presence of humans as a blood source. Carbon dioxide acts as a respiratory signal that can trigger host-seeking activity, while human body odor, including lactic acid, strengthens mosquito orientation toward the stimulus source. Understanding these sensory mechanisms provides the basis for developing attractant-based traps that mimic the presence of a human host (13, 25, 26).

Lactic acid was the most effective single attractant in this study. This result is consistent with the concept that lactic acid is one of the components of human body odor recognized by mosquitoes during host seeking. CO_2 also makes an important contribution because it functions as a chemical cue indicating human presence through respiration. The combination of CO_2 and lactic acid may influence mosquito orientation toward the trap; however, the observed effect depended on the specific multimodal combination used in this study (14, 15, 18, 27).

From a practical perspective, the relatively high effectiveness of lactic acid alone should also be considered when evaluating the economic value of the four-mode system. Although the four-mode combination achieved the highest mean effectiveness, future studies should compare the additional benefit of multimodal integration with device complexity, energy requirements, maintenance demands and production cost. A simpler lactic-acid-based system may be more feasible in some settings if its effectiveness is sufficient for the intended application.

Ultraviolet-A light and sound frequency function as physical stimuli that complement the activity of chemical attractants. Ultraviolet-A light assists the visual orientation of mosquitoes toward a light source, while sound frequencies within a certain range can influence flight activity and acoustic responses. When ultraviolet-A light and sound frequency are combined with carbon dioxide and lactic acid, the trap provides more complex stimulation, thereby increasing the likelihood that mosquitoes will approach the trap area. This condition enables the suction fan and electric shock system to work more effectively in capturing or electrocuting mosquitoes (16, 17, 28).

The four-mode combination, consisting of ultraviolet-A light, sound frequency, carbon dioxide and lactic acid, produced the highest effectiveness compared with single attractants and two- or three-mode combinations. This finding supports the concept of multimodal integration, in which mosquito responses to hosts are influenced by the simultaneous combination of multiple environmental cues. However, because some three-mode combinations did not outperform lactic acid alone, the benefit of multimodal integration appears to depend on the specific composition and configuration of stimuli rather than the number of modalities alone (21, 22, 29).

The results of this study showed that the multimodal trap performed significantly better than the Mosquito Killer BG-360 and the suction-only negative control. These findings suggest that trap design, attractant composition, and the ability of the device to direct mosquitoes toward the capture system may influence trap performance. Although the multimodal trap showed a numerically higher mean number of captured or electrocuted mosquitoes than the Photocatalyst Mosquito and Fly Trap, the difference was not statistically significant ($p= 0.141$). Therefore, superiority over the Photocatalyst Mosquito and Fly Trap cannot be concluded. Previous evaluations of mosquito traps have also shown that trap success is influenced by device design, attractant composition, capture mechanism and the ecological context in which the trap is applied (30–33).

The relevance of this study to vector-borne disease control lies in the potential contribution of a non-insecticide trap to adult *Ae. aegypti* management as part of integrated vector control. In dengue-endemic settings, vector control programs cannot rely solely on fogging or chemical insecticides, particularly when insecticide resistance and repeated chemical exposure are growing concerns. Several studies in Indonesia have reported reduced susceptibility or resistance of *Ae. aegypti* to commonly used insecticides, including pyrethroids and organophosphates. Therefore, a trap-based strategy using multimodal attractants may provide an additional tool for reducing adult *Ae. aegypti* populations in domestic and peri-domestic environments without directly increasing insecticide selection pressure (10–12).

The development of the multimodal trap is also consistent with the principles of integrated vector management, which emphasize the use of combined environmental, physical-mechanical, biological and technological approaches for vector control. Source reduction remains important for dengue prevention, but its effectiveness depends greatly on sustained community participation, household monitoring and environmental management. In this context, a non-insecticide multimodal trap may serve as a supporting technology that works more practically and measurably to reduce adult mosquito populations (4, 7, 8).

However, this study has several limitations. First, testing was conducted only under laboratory and enclosed-room conditions; therefore, the findings may not directly reflect trap performance under semi-field or field conditions. Second, the study evaluated short-term captured or electrocuted mosquito outcomes and did not assess reductions in adult mosquito density, dengue transmission, or long-term trap durability. Third, the effectiveness of the system may have been influenced by environmental conditions, trap placement, attractant release characteristics and mosquito physiological status. Fourth, the study did not evaluate non-target insect capture, household acceptability, energy consumption, maintenance requirements, or cost-effectiveness. Although the electric-shock output was technically measured, household electrical safety, user acceptability, energy consumption, maintenance requirements and long-term operational safety were not evaluated; therefore, further safety assessment is required before wider deployment. A true no-trap/no-attractant negative control with the prototype powered off was not included; therefore, spontaneous mosquito mortality independent of prototype operation could not be quantified. Finally, because not all multimodal combinations improved performance, further studies are needed to optimize the composition, concentration, timing and arrangement of individual stimuli.

Conclusion

This study developed and evaluated a non-insecticide multimodal trap integrating carbon dioxide, lactic acid, ultraviolet-A light, sound frequency, a suction fan and an electric shock system for *Ae. aegypti* control. A 10% lactic acid solution and the selected 10% liquid CO_2 formulation produced the highest responses in the attractant test. The four-mode combination of ultraviolet-A light, sound frequency, carbon dioxide and lactic acid produced the highest effectiveness, with a mean of 45.66 captured or electrocuted mosquitoes, corresponding to 91.33% effectiveness and a maximum observed value of 98%. In the enclosed-room test, the multimodal trap performed significantly better than the Mosquito Killer BG-360 and the suction-only negative control, while its difference from the Photocatalyst Mosquito and Fly Trap was not statistically significant. These findings suggest that the multimodal trap may serve as a supporting non-insecticide-based tool for adult *Ae. aegypti* vector control. Further research should include semi-field and field trials, design refinement, durability testing, safety assessment and operational feasibility evaluation.

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Ethical considerations

This study used laboratory-reared Ae. aegypti mosquitoes as experimental subjects and was approved by the Ethics Committee of the Faculty of Medicine, Public Health and Nursing, Universitas Gadjah Mada, Indonesia, with approval number KE/FK/0941/EC/2019. All laboratory procedures were conducted in accordance with biosafety, containment, and responsible mosquito-handling practices.

Conflict of interest statement

The authors declare that there is no conflict of interest.

Declaration of artificial intelligence use

Artificial intelligence tools were used only to assist with language editing and manuscript formatting. The authors reviewed, verified, and approved all content and remain fully responsible for the accuracy and integrity of the manuscript.

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