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EXPERIMENTAL THERMAL CHARACTERIZATION OF A RAPHIA FIBER–INSULATED PASSIVE COOLING BAG FOR VACCINE COLD CHAIN PRESERVATION UNDER TROPICAL CONDITIONS

*Caractérisation thermique expérimentale d'un sac autocuiseur isolé en fibres de
raphia pour la conservation de la chaîne du froid vaccinale en conditions
tropicales.*

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1. RÉSUMÉ / ABSTRACT

Résumé (Français) — Calibri 10 pt — interligne simple

Le maintien de la chaîne du froid vaccinale constitue un défi majeur pour les systèmes de santé des pays à ressources limitées, en particulier dans les zones tropicales soumises à de fortes contraintes climatiques et

énergétiques. Ce travail évalue les performances thermiques d'un sac autocuiseur isolé, initialement conçu pour la cuisson par rétention de chaleur, comme dispositif alternatif de conservation des vaccins entre 2 °C

et 8 °C. Le sac est constitué d'une enveloppe externe en tissu de coton wax et d'une couche interne isolante en fibres de raphia vinifera. Une démarche mixte, combinant approches expérimentale, analytique et numérique, a été adoptée. Des essais ont été menés en laboratoire puis en conditions réelles (jusqu'à 60 °C en surface), avec variation de la masse de glace, utilisation d'accumulateurs de froid et introduction de flacons de vaccins simulés. Les résultats montrent que le dispositif maintient une température interne comprise entre 1,7 °C et 3 °C pendant plus de 11 heures en conditions douces et jusqu'à 9 heures en conditions extrêmes, validant son aptitude à couvrir une journée de vaccination. Les fibres de raphia présentent une faible conductivité thermique comparable à celle de matériaux isolants conventionnels. Ce dispositif low-cost, indépendant de l'électricité et fabriqué à partir de ressources locales, constitue une alternative prometteuse aux porte-vaccins synthétiques pour les zones rurales tropicales à infrastructure limitée.

Abstract (English) — Calibri 10 pt — single spacing

Maintaining the vaccine cold chain remains a major challenge for health systems in resource-limited countries, particularly in tropical regions facing severe climatic and energy constraints. This study evaluates the thermal performance of an insulated cooling bag, originally designed for retained-heat cooking, as an alternative device for preserving vaccines between 2 °C and 8 °C. The bag consists of an outer layer of 100% cotton wax fabric and an inner insulating layer made of raphia vinifera fibers. A mixed methodological approach combining experimental, analytical and numerical methods was adopted. Tests were conducted first under laboratory conditions and then under real tropical conditions (surface temperatures up to 60 °C), varying the ice mass, using cold accumulators, and introducing simulated vaccine vials. Results show that the device maintains an internal temperature between 1.7 °C and 3 °C for more than 11 hours under mild conditions and up to 9 hours under extreme conditions, confirming its suitability for a full day of vaccination activities. Raphia fibers exhibit low thermal conductivity, comparable to conventional insulating materials. This low-cost, electricity-independent device, manufactured from locally available resources, constitutes a promising alternative to synthetic vaccine carriers for rural tropical areas with limited infrastructure.

Keywords: Vaccine cold chain; thermal insulation; raphia vinifera fiber; passive cooling; tropical conditions; biosourced material; vaccine carrier

2. INTRODUCTION

Vaccination remains one of the most cost-effective public health interventions, preventing several million deaths every year worldwide. Its effectiveness, however, depends critically on maintaining vaccines within the temperature range recommended by the World Health Organization (WHO), generally between +2 °C and +8 °C, from the manufacturing site to the point of administration [1]. Any deviation from this range, whether by exposure to heat or to freezing temperatures, can significantly reduce vaccine potency and compromise immunization campaigns [15].

In low- and middle-income countries, and particularly in tropical regions such as Cameroon, maintaining an uninterrupted cold chain is a persistent challenge. Frequent power outages, high ambient temperatures that can exceed 50–60 °C during the hottest months, long transport distances to rural health centres, and the high cost of synthetic vaccine carriers all contribute to frequent cold chain failures [5], [6]. Passive cooling devices vaccine carriers and cold boxes relying solely on ice or cold accumulators remain the most accessible solution in such contexts because they do not depend on electricity [4]. However, most commercially available carriers

use synthetic insulating materials (expanded polystyrene, polyurethane) that are costly and difficult to source locally, and their performance is generally validated only under WHO Performance, Quality and Safety (PQS) laboratory conditions, capped at 43 °C, which do not reflect the extreme ambient temperatures observed on the field in tropical Africa [2], [8].

To address this gap, the present work investigates the thermal performance of a locally manufactured "autocuiseur" bag originally designed as a retained-heat cooking device repurposed as a passive vaccine carrier. The bag combines an external layer of 100% cotton wax fabric with an internal insulating layer made of raphia vinifera fibres, a biosourced, biodegradable and low-cost natural material widely available in Cameroon. Unlike most previous studies, the experimental protocol adopted here was not restricted to controlled laboratory conditions but also included tests carried out under real tropical conditions, with ambient surface temperatures reaching up to 60 °C.

The main objective of this study is to determine whether the raphia-based Cooling Bag can maintain the internal temperature within the WHO-recommended 2–8 °C range for a duration compatible with a full working day of vaccination activities (approximately 8 to 10 hours), using either ice or cold accumulators, and in the presence of simulated vaccine vials.

The remainder of this paper is organised as follows. Section 3 reviews the relevant literature on vaccine cold chain equipment and insulating materials. Section 4 describes the materials, the experimental setup and the methodology adopted. Section 5 presents the experimental results, which are discussed in Section 6. Section 7 concludes the paper and outlines perspectives for future work.

3. LITERATURE REVIEW / STATE OF THE ART

3.1 Previous Works

Vaccine cold chain management has been extensively studied from both technological and material perspectives. The WHO PQS programme defines standardized testing protocols for vaccine carriers and cold boxes, including cold-life tests, heat-load tests and freeze-prevention tests, generally conducted at a maximum ambient temperature of 43 °C [2]. Ng et al. [2] evaluated several vaccine carrier configurations and showed that polystyrene foam boxes sealed with at least five ice packs, and larger cold boxes with polyethylene liners and polypropylene insulation, could maintain vaccines within the required range for extended periods. Ashok et al. [4] highlighted persistent structural weaknesses of existing carrier designs for rural distribution, notably their limited autonomy and their dependence on a continuous supply of frozen ice packs.

From a materials perspective, Pambudi et al. [3] reviewed cold storage technologies for vaccines and reported that conventional WHO-type polyurethane/expanded polystyrene carriers offer an autonomy of 12 to 24 hours between 2 and 8 °C, but that up to 50% of the cooling capacity can be lost due to freezing or heat exposure in low-income countries. Phase Change Materials (PCM) have attracted growing interest as an alternative: Zhao et al. [11] combined tetradecane and lauryl alcohol to maintain vaccine storage temperature between 2 and 8 °C, while Devrani et al. [7] showed that a cylindrical vaccine carrier integrating PCM improved cold-life duration by 17% and thermal resistance by 16% compared to a conventional cubic design. Gan et al. [12] further demonstrated that the number and spatial arrangement of cold packs strongly influence the thermal homogeneity and autonomy of portable cold storage boxes, reaching up to 27 hours of conservation with optimized PCM configurations.

Natural fiber-based insulating materials have also been explored as low-cost, biodegradable alternatives to synthetic insulation. Pickering et al. [10] reviewed the mechanical and thermal properties of natural fibers composites, underlining their favourable insulation potential and environmental benefits; raphia vinifera fibers in particular have been shown to exhibit low thermal conductivity due to their fibrous structure rich in air cavities, conferring good insulating capacity.

Regarding field validation, Kumar et al. [13] evaluated freeze-preventive, WHO-prequalified cold boxes under real conditions in rural Nepal and emphasised the role of an insulating barrier between cold accumulators and vaccine vials to avoid freezing. Falcón et al. [9] conducted a field temperature-monitoring study of the vaccine

cold chain in Mexico and reported frequent temperature excursions outside the recommended range, confirming a gap between laboratory-validated performance and real-world conditions. In Cameroon specifically, Yauba et al. [5] and Asamoah et al. [6] documented frequent cold chain temperature deviations linked to power outages and inadequate handling practices, further motivating the search for robust, locally manufactured, electricity-independent solutions.

3.2 Positioning of the Contribution

While the literature confirms the effectiveness of PCM-enhanced and synthetic vaccine carriers, these solutions remain costly and difficult to access in resource-limited tropical settings. Moreover, most reported experimental protocols are restricted to controlled laboratory conditions not exceeding 43 °C, which does not reflect the extreme ambient temperatures up to 60 °C observed in tropical field conditions. This study distinguishes itself by (i) repurposing an existing, locally manufactured device (the raphia-based Cooling Bag) rather than designing a new carrier from scratch, (ii) relying exclusively on low-cost, biosourced raphia vinifera fibres as insulating material, and (iii) validating the device under both laboratory and real tropical field conditions, including with simulated vaccine vials, providing a more representative assessment of its applicability for rural immunization campaigns in Cameroon.

4. MATERIALS AND METHODS

4.1 Description of Materials / System

The device under study is a locally manufactured cylindrical "autocuiseur" bag, originally designed to complete food cooking through retained heat and repurposed in this study as a passive vaccine carrier (see Figure 1). It is a multilayer bag: the outer layer is made of 100% cotton wax fabric, chosen for its flexibility, mechanical resistance and availability, while the inner insulating layer is made of raphia vinifera fibres arranged in panel form. The bag has an external diameter of 20 cm, an internal diameter of 30 cm, an internal height of 25 cm and an external height of 15 cm, giving an internal volume of 4.71 L, and an empty mass of 5.165 kg. It includes a hermetic lid, a sealed closure and a carrying handle.

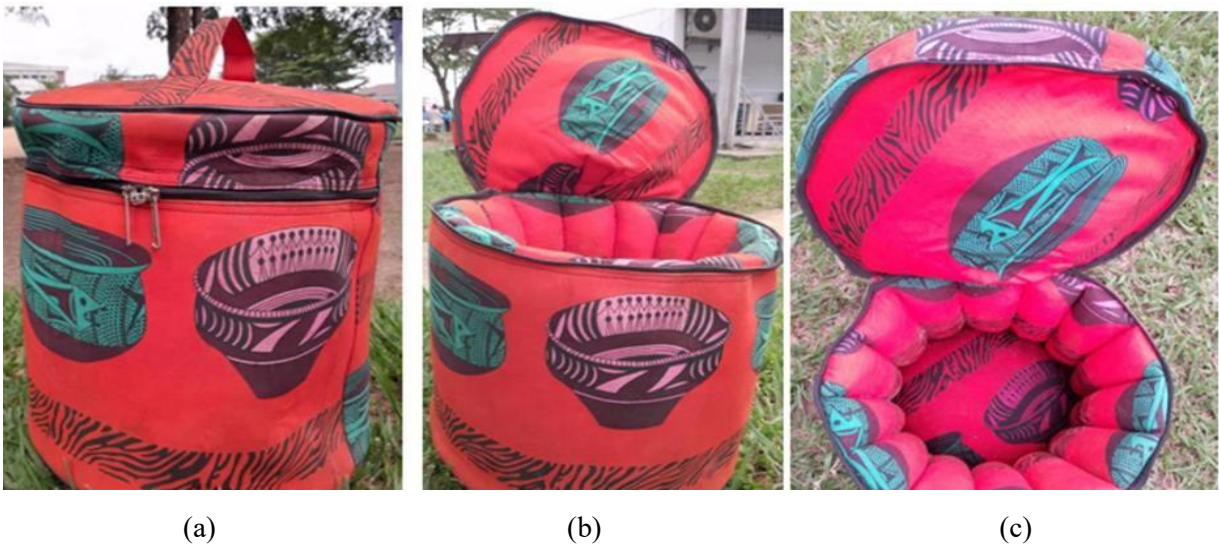


Figure 1 — General view, open bag and internal structure of the Cooling Bag Table 1 — Technical characteristics of the instrumentation used

Equipment	Description	Key specifications
Temperature datalogger	USB-connected K-type thermocouple recorder	±0.5 °C accuracy; –35 to 80 °C range
Thermocouple probe	Point temperature measurement	–200 to 1250 °C; ≈41 µV/°C sensitivity

Cold accumulator	Reusable gel-based cold pack	Mass: 690 g each
Ice block	Frozen tap water	1.5 L bottles
Precision balance	Mass measurement of ice / accumulators	±1 g; 10 kg capacity

4.2 Methodology / Approach

A mixed-method approach was adopted, combining: (i) an experimental method to observe and measure the thermal behaviour of the bag under controlled and real conditions; (ii) an analytical method, based on heat transfer equations (conduction, thermal resistance, energy balance) to model the system; and (iii) a numerical method, using MATLAB (R2016b) for data processing and simulation and Microsoft Excel for data acquisition, organisation and pre-processing. The overall experimental protocol is summarised in the synoptic diagram of Figure 2.

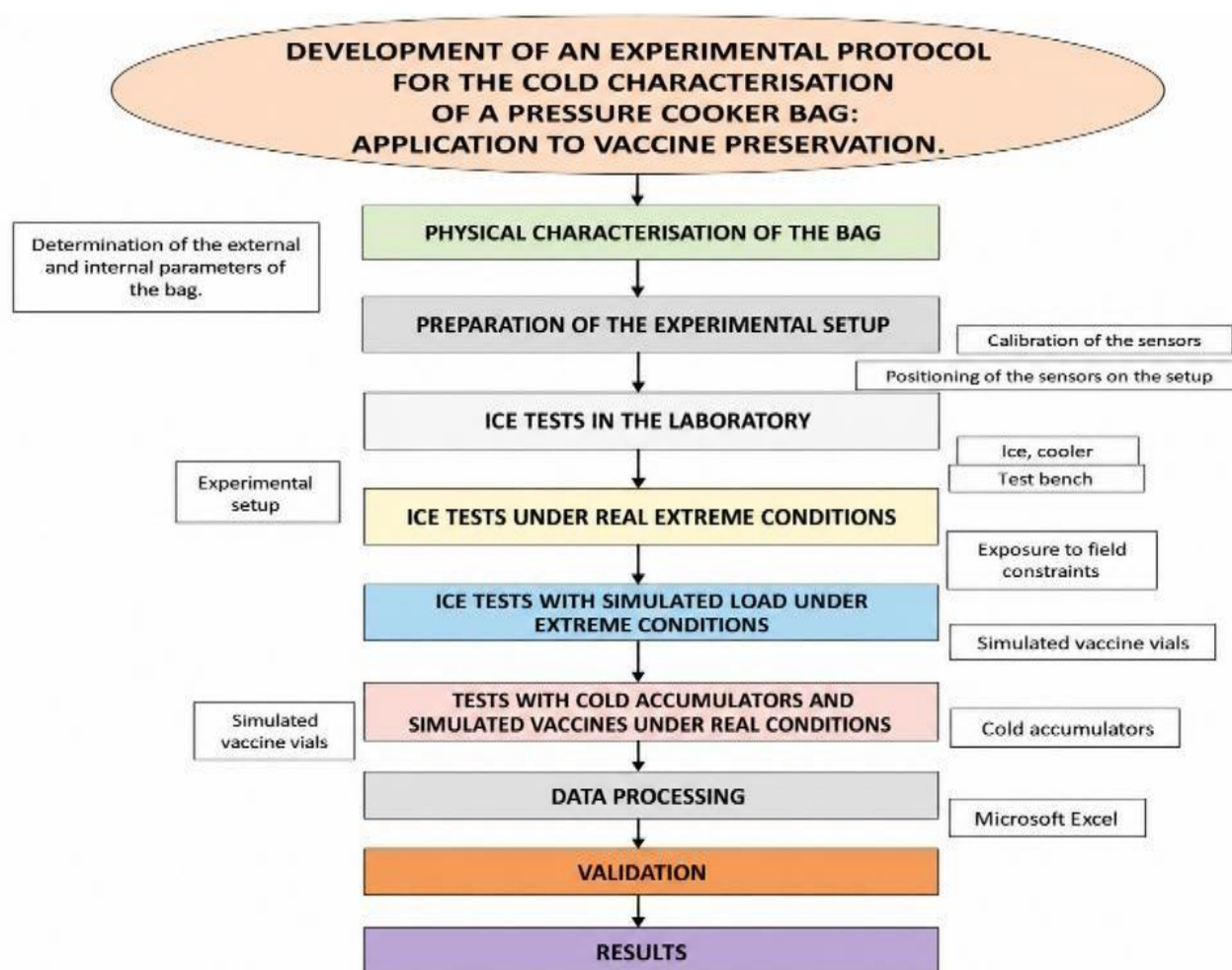


Figure 2 — Synoptic diagram of the experimental test sequence

4.2.1 Algorithm Experimental Protocol (Test Sequence)

Prior to each test, temperature sensors were positioned at several external and internal locations on the bag, and both the sensors and the precision balance were calibrated. Four series of tests were then conducted: (1)

ice-based tests under mild, controlled laboratory conditions, with ice mass varied from 500 g to 3254 g over six sessions; (2) ice-based tests under real, extreme tropical conditions (open air, direct solar radiation), with ice mass varied from 1500 g to 2500 g over three sessions, ambient surface temperatures reaching up to 60 °C; (3) tests under real conditions with simulated vaccine vials (pre-cooled to 2 °C) placed inside the bag, protected from direct contact with the ice by a sealed plastic film, in accordance with WHO recommendations to prevent freezing; and (4) tests under real conditions using cold accumulators (four to five units of 690 g) instead of ice, combined with simulated vaccine vials. Internal and external temperatures were recorded at 3-minute intervals throughout each test.

4.3 Performance Indicators

The thermal performance of the bag was assessed using the following indicators, consistent with WHO PQS testing philosophy: (i) cold-life duration, defined as the time during which the internal/vaccine temperature remains within the 2–8 °C range; (ii) compliance with the target temperature range under both mild and extreme ambient conditions; (iii) occurrence of freezing events (temperature below 0 °C at the vaccine location); (iv) repeatability of results across repeated trials; and (v) sensitivity of performance to the cooling mass (ice or accumulators) used.

5. RESULTS

5.1 Thermal Behaviour Under Laboratory (Mild) Conditions

Under laboratory conditions (ambient temperature 27–38 °C), the internal probe (ice compartment) remained remarkably stable, between 1.8 °C and 3 °C, for durations ranging from 5h10 to 11h33 depending on the ice mass used (see Figure 3 for a representative temperature profile). The largest ice mass tested (3254 g) allowed the internal temperature to remain stable for approximately 9 hours, with 2267 g of ice still remaining at the end of the test and 621 g remaining 24 hours later, confirming the low thermal diffusivity of the raphia insulation. Conversely, the lowest ice masses (500 g and 1000 g) led to premature temperature rises above 8 °C or to early test termination due to complete ice melting, before the intended duration was reached. Surface sensor readings exhibited limited dispersion, indicating good thermal homogeneity across the bag, and tended to converge once the ice was fully melted. Overall, these results confirm that the raphia/cotton wax combination limits heat exchange with the external environment and that, provided the ice mass is at least 1500 g, the bag can maintain the target range for more than 7 hours, sufficient for a typical vaccination working day.

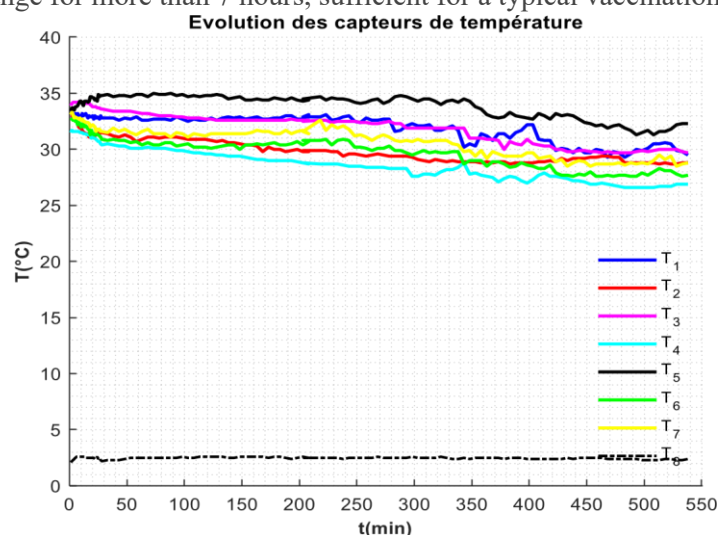


Figure 3 —Representative thermal evolution of the bag during a laboratory test (3254 g of ice)

5.2 Thermal Behaviour Under Real (Extreme) Conditions and With Simulated Vaccines

Under real tropical field conditions, with ambient surface temperatures reaching up to 60 °C, the internal probe remained between 1.7 °C and 2.3 °C for durations of 7h30 to 8h, depending on the ice mass (1500–2500 g), despite pronounced oscillations in the external sensor readings caused by direct solar exposure. When simulated vaccine vials (pre-cooled to 2 °C) were introduced, their temperature remained between 2 °C and 3

°C for more than 7 hours, showing that the presence of the vials did not significantly alter the ice melting rate an important validation for the intended vaccine-carrier application. Tests using cold accumulators produced comparable results: with five accumulators, the vaccine-vial temperature remained within range beyond the intended duration; with four accumulators pre-cooled to 0 °C, conservation lasted 7h30 with the target range fully respected; however, when accumulators were only pre-cooled to 2.5 °C due to power interruptions, the target range was broken after 8 hours. Table 2 summarizes the results obtained across all four test series.

Table 2 — Summary of experimental test results across the four-test series

Test conditions	Cooling mass	Ambient temp. range	Internal / vaccine temp.	Duration in range
Laboratory (mild)	500 – 3254 g ice	27 – 38 °C	1.8 – 3 °C	up to 11h33
Real (extreme)	1500 – 2500 g ice	28 – 60 °C	1.7 – 2.3 °C	7h30 – 8h
Real + simulated vaccines	Ice, protected by film	up to 60 °C (surface)	2 – 3 °C	> 7h
Real + cold accumulators + vaccines	4–5 × 690 g	27 – 40.5 °C	≈ 3 °C (stabilised)	7h30 – 9h

6. DISCUSSION

The results obtained in laboratory (mild) conditions confirm the first research hypothesis: the raphia-based Cooling Bag is capable of maintaining the internal temperature between 2 °C and 8 °C for more than 11 hours, comparable to the 12–24-hour autonomy reported by Pambudi et al. [3] for conventional WHO polyurethane/expanded polystyrene carriers, but achieved with a considerably lower-cost, locally sourced material. The dependence of cold-life duration on ice mass observed here (about 9 hours for 3254 g, shorter for lower masses) is consistent with the findings of Gan et al. [12] and Ng et al. [2], who showed experimentally that the quantity and arrangement of cold packs strongly influence the thermal performance of vaccine carriers; the 27-hour autonomy reported by Gan et al. [12], however, was achieved using specialised phase-change materials substantially more expensive than locally sourced ice.

A key contribution of this study is the validation of the device under real tropical conditions, with ambient surface temperatures reaching 60 °C, well beyond the 38–43 °C ceiling typically used in WHO PQS and related laboratory protocols [2]. This gap between laboratory validated and field performance had already been highlighted by Falcón et al. [9], who reported frequent temperature excursions outside the recommended range during field monitoring in Mexico. Despite these extreme conditions, the internal temperature of the Cooling Bag remained stable between 1.7 °C and 2.2 °C, confirming the low thermal conductivity of raphia vinifera fibres, in line with earlier characterisations of natural fibre insulation [10].

The introduction of simulated vaccine vials did not significantly affect cold-life duration, supporting the direct applicability of the device to vaccine conservation and echoing the precautionary approach — using a plasticfilm barrier to prevent freezing contact — recommended and validated in the field by Kumar et al. [13] for WHO-prequalified freeze-preventive cold boxes. The comparison between ice and cold accumulators showed similar overall performance, but revealed a critical limitation: when accumulators were insufficiently precooled due to power outages, the temperature range was broken. This finding corroborates observations by Ashok et al. [4] and Yauba et al. [5], who identified unreliable electricity supply as one of the main causes of cold chain failure in low-income settings, and reinforces the practical advantage of ice, which does not depend

on a functioning freezer at the point of use, as the more robust option in electricity-constrained rural areas — while acknowledging that ice availability itself can be seasonally limited.

Several limitations must be acknowledged. Sensor malfunctions affected the completeness of some recordings, and testing was limited to a single prototype, whereas WHO PQS protocols require a minimum of two samples to establish repeatability. Future work should therefore include a second prototype, as well as the integration of biosourced phase-change materials, which prior studies suggest could extend cold-life duration by up to 17% [7] or more with optimized spatial configuration [12].

7. CONCLUSION

This study experimentally characterised the thermal performance of a raphia-fibre-insulated Cooling Bag as a low-cost, electricity-independent alternative for vaccine cold chain preservation in tropical settings. Under laboratory conditions, the device maintained the WHO-recommended 2–8 °C range for more than 11 hours, and under real tropical conditions — with ambient surface temperatures reaching 60 °C — for up to 9 hours, using either ice or cold accumulators. The presence of simulated vaccine vials did not compromise these performances, and no freezing events were recorded when the recommended plastic-film barrier was used, directly addressing the research question of whether this repurposed device can serve as a viable vaccine carrier. These results validate the first two research hypotheses and confirm that raphia vinifera, a biodegradable and locally available natural fibre, offers insulating performance comparable to conventional synthetic materials at a substantially lower cost.

Given the persistent challenges of unreliable electricity supply and the high cost of imported synthetic vaccine carriers in tropical low-resource settings, the raphia-based Cooling Bag represents a promising, sustainable and accessible contribution to last-mile vaccine delivery. Future work will focus on testing a second prototype in accordance with WHO PQS repeatability requirements, integrating biosourced phase-change materials to further extend autonomy, and conducting extended field trials across different seasons and health districts to confirm the operational robustness of the device under routine immunization campaign conditions.

8. ACKNOWLEDGEMENTS

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