



Regular Research Article

Comparative Thermal Performance Analysis of Nipah Palm Fiber and Expanded Polystyrene as Sustainable Cool Box Insulation for Small-Scale Fisheries

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Abstract: Small-scale fishermen in the Sangihe Islands rely heavily on expanded polystyrene (EPS) cool boxes to preserve fish during transit, yet these synthetic materials are environmentally problematic and economically limiting. This study experimentally evaluates Nipah palm fiber (*Nypah fruticans*), an abundant coastal biomass waste, as a sustainable insulation alternative for pumpboat-based fisheries. Three cooler box configurations were comparatively tested under controlled tropical conditions ($31^{\circ}\text{C} \pm 2^{\circ}\text{C}$ ambient temperature) over a 12-hour period: (1) standard EPS insulation (20 mm), (2) raw compressed Nipah fiber (30 mm), and (3) a hybrid composite combining compressed Nipah fiber (30 mm) with a reflective aluminum layer. Thermal performance was assessed through continuous internal, external, and fish-core temperature monitoring at 30-minute intervals. Results demonstrate a clear hierarchy in insulation efficiency. The hybrid Nipah configuration achieved the lowest warming rate ($0.167^{\circ}\text{C}/\text{hour}$), nearly three times slower than the EPS control. After 12 hours, the hybrid system-maintained fish temperature at 0.4°C , compared to 4.8°C in the EPS box. The improved performance is attributed to the dense lignocellulosic fiber structure, which enhances air entrapment and reduces conductive heat transfer, while the aluminum layer minimizes radiant heat gain. These findings confirm that Nipah palm waste provides a cost-effective, locally available, and environmentally sustainable insulation solution tailored to tropical maritime logistics. The adoption of Nipah-based bio-composite insulation has the potential to extend fish shelf life, reduce post-harvest losses, and decrease dependence on non-biodegradable synthetic polymers in traditional fisheries.

Keywords: Cool box, Thermal Performance, Heat Transfer Rate, Nipah Fiber, Sustainable Insulation.

1. Introduction

The Sangihe Islands Regency possesses significant capture fisheries potential, with a recorded production of over 14.9 million kg in 2021 [1]. Despite this abundance, small-scale fishermen operating "pumpboats" face critical challenges in maintaining catch quality due to inadequate onboard storage [2]. Post-capture spoilage is primarily driven by thermal fluctuations during transit, necessitating efficient insulation systems.

Pumpboats are a fishing fleet that is widely used by Sangihe Island fishermen. The application of technology both in terms of construction and use, fishermen in Sangihe adopted technology from Filipino fishermen. The main material selection for a pumpboat consists of the body, superstructure and steering system. Outrigger boats are included in the category of traditional fishing boats, because their construction is based on the experience and expertise passed down from generations of the Sangihe tribe, the keel and

tusks are made of wood, the hull and superstructure are made of special playwood, and bamboo in the katir system [3].



Figure 1. Pumpboat in Sangihe

Pumpboats play a central dual role for the coastal communities of the Sangihe Islands: as a means of inter-island transportation and as a primary means of fishing. Due to their vital role, pumpboats have become an integral part of the daily lives of the Sangihe people. These vessels are generally equipped with two types of holds (fish cargo spaces): a permanent hold, usually located in the center of the boat, and a non-permanent hold, which is a Styrofoam cool box or a plywood hold lined with Styrofoam.

The hold is the part of a vessel that serves as a container for storing the fish catch and is usually equipped with a hold insulation system that prevents external heat from entering the hold [4].

The use of premium insulation materials, such as polyurethane, presents a high production cost barrier for small-scale fishermen. In addition to being relatively expensive, its availability is also very limited in local markets, such as in the Sangihe Islands Regency. Although some fishermen near ice factories have tried adding dry ice to extend the temperature in the cargo hold, this method has significantly increased vessel operating costs. Therefore, fishermen generally rely on readily available Styrofoam cool boxes. However, if the quantity or size of the fish caught exceeds the capacity of the available cool box, the catch is often left untreated without ice, which risks compromising its quality.

Post-catch fish handling is an activity aimed at maintaining the quality of fish from the moment it is caught until it is consumed [5]. In practice, this means slowing or stopping spoilage, preventing contamination, and avoiding physical damage to the catch. This practice is carried out almost daily by small-scale fishermen in the Sangihe Islands.

2. Materials and Methods

In this study, the test material used was natural fiber which can be found along the coast of the Sangihe Islands. Natural fibers are fibers made from natural ingredients such as palm. Nipah (*Nypah fruticans* Wurmb.) has many functions and benefits [6]. Several areas in Papua which have abundant nipah populations generally use leaf midribs and leaf veins as construction materials for house walls. Nipah fronds are a ligno-cellulosic fiber material, so it is hoped that it can be used to make pulp, paper and cellulose derivatives. others, including fiberboard.

Currently, fishermen rely heavily on Expanded Polystyrene (EPS/Styrofoam) or expensive Polyurethane (PU) foam. However, the high cost and limited local availability of PU, combined with the environmental footprint of EPS, create a demand for accessible, bio-based alternatives. While previous studies have explored natural fibers like coconut husk or

durian peel, the specific application of Nipah palm fiber (*Nypah fruticans*) which is abundant and underutilized in the Sangihe coastal ecosystem remains under-researched.

Nipah fronds contain high ligno-cellulosic content, offering promising thermal resistance properties similar to Medium-Density Fiberboard (MDF) materials [7]. This study aims to bridge the research gap by providing a quantitative experimental comparison between traditional insulation and Nipah-based composites. The novelty lies in the optimization of Nipah fiber density to enhance the thermal lag in tropical maritime environments, specifically tailored for the operational constraints of Sangihe's traditional pumpboats.

Although fish coolers (cool boxes) show adequate thermal efficiency in maintaining low internal temperatures, the production costs arising from the use of synthetic materials such as polyethylene and fiberglass are relatively high, thus directly increasing the capital expenditure in the construction of fishing vessel cargo spaces [8].

Therefore, there is an urgent need to

identify and utilize alternative raw materials that are abundant and economical [9]. Natural biomass-based materials, such as coconut fiber, sawdust, and rice bran, offer promising solutions as alternative thermal insulators. These materials were chosen because they have relatively low thermal conductivity (k) [10], a physical property that is essential for minimizing the rate of heat transfer and maintaining cool conditions effectively. In addition, based on previous research results, the main advantages of natural fibers are their low environmental impact, low cost, and can even compete with commercialized synthetic materials [11].

2.1. Material Selection and Preparation

The selection of Nipah palm fiber over other natural fibers is based on its high silica content and hollow cellular structure, which provides inherent low thermal conductivity. Unlike coconut fiber, which is often repurposed for industrial textiles, Nipah fronds in Sangihe are currently treated as agricultural waste, making them a zero-cost insulation substrate.



Figure 2. Palm on the coast of Sangihe

In this research, the method was based on an experimental evaluation of cool box insulation performance for preserving caught fish, followed by a qualitative descriptive analysis of the observed thermal behavior. A comparative assessment was conducted between a factory-made cool box (EPS), a

cooling hatch insulated with sawdust based on previous studies, and a hatch insulated with Nipah palm fiber developed in this study.

Figure 3 illustrates the cross-sectional configuration of the natural fiber-insulated cool box. The schematic shows the double-wall plywood structure and the insulation cavity

filled with compressed Nipah fiber composite. This cross-sectional representation clarifies the spatial arrangement of the insulation layer, the thickness distribution, and the structural interface between the inner storage chamber and the external wall. By visualizing the layered construction, the figure highlights how the insulation material functions as a thermal barrier that reduces conductive and radiant heat transfer from the ambient environment into the storage compartment.

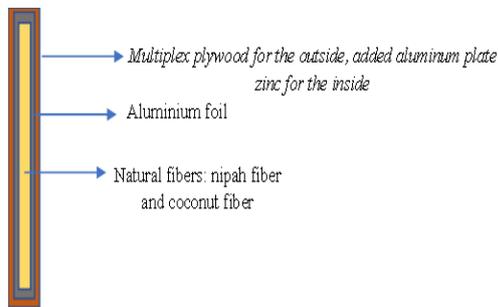


Figure 3. Cross-section of the cool box natural fiber insulation

2.2. Experimental Setup and Boundary Conditions

To ensure a systematic and controlled comparison, three cool box configurations were designed and fabricated. The first configuration served as the control, consisting of a standard plywood box insulated with 20 mm expanded polystyrene (EPS). The second configuration (Type A) used a 30 mm layer of compressed

Nipah palm fiber as the sole insulation material. The third configuration (Type B – Hybrid) incorporated a 30 mm compressed Nipah fiber layer combined with a reflective aluminum plate to enhance resistance against radiant heat transfer.

All experimental tests were conducted under controlled boundary conditions, with an average ambient temperature of 31°C (±2°C). A constant ice-to-fish mass ratio of 1:1 was maintained across all configurations to ensure comparability of thermal loads. Each cool box was filled with 10 kg of ice, and temperature monitoring was performed over a continuous 12-hour period. Temperature data were recorded using TPM-10 digital thermometers equipped with Negative Temperature Coefficient (NTC) thermistor probes. These waterproof metal probes, connected via 1-meter cables, allowed continuous measurement of internal temperature without opening the cool boxes, thereby preventing external thermal disturbance. The sensors operate within a measurement range of -50°C to +110°C.

Prior to testing, all sensors were calibrated using the ice-point method (0°C) to ensure measurement reliability. Although the devices provide a nominal resolution of 0.1°C, an experimental tolerance margin was considered to account for the inherent accuracy limitations of NTC-based thermistors under field conditions. The detailed specifications and configuration parameters of each experimental cooling box are summarized in Table 1.

Table 1. Specification and Configuration of Experimental Cool Boxes

Box ID	Core Insulation Material	Thickness (mm)	Density (kg/m ³)	Additional Layer	Purpose
Box 1 (Control)	Expanded Polystyrene (EPS)	20	~15	None	Baseline for existing local methods
Box 2	Raw Nipah Palm Fiber	30	~120	None	Evaluating raw natural fiber performance
Box 3 (Hybrid)	Compressed Nipah Fiber	30	~150	Aluminum Foil	Maximizing thermal resistance (R-Value)

3. Results

3.1 Material Preparation

The preparation of the Nipah palm fiber insulation was conducted through three main

stages: material preparation, moisture reduction, and composite fabrication.

- Basic Material Preparation: This stage begins with cleaning the palm palm branches of any

dirt. The branches are then precisely cut to the specific length and width of the thermal insulation model to be created.

- **Drying Treatment** To ensure optimal insulation performance, the palm base material must reach a low moisture content or anhydrous state. The drying process is carried out by exposing it to direct sunlight for three consecutive days. The purpose of this drying process is to reduce the water content in the palm fibers.
- **Fabrication and forming**, which is the process of structurally forming the base material into an insulation block with predetermined dimensions. Polyurethane (PU) glue is applied as a binder in measured quantities. This process aims to achieve optimal material

cohesion, forming a good, solid structure according to the size of the designed insulation space

The size of the fish cooler box made was 2 units Length 40cm x wide 31 cm x height 31 cm with 3 different treatments. The outer and inner wall boxes were purchased from the market made of multiplex plywood. Then the walls are filled with palm fiber which has been mixed with polyurethane. The insulator chamber is constructed after the material has been formed. The next step is to cut the plywood to the desired dimensions. The fish cooler box measures (L) 40 cm x (W) 31 cm x (H) 31 cm, two units of which are treated differently. The outer and inner walls of the box are made of 6 mm plywood. The inner walls are then filled with dry palm fiber mixed with a binder.



Figure 4. Material preparation and cool box assembly

3.2. Testing the Cool Box

The thermal performance test was conducted in the Fishing Technology Laboratory workshop under controlled indoor conditions for a total duration of 12 hours. Each cool box was instrumented with three digital thermometers. One sensor was placed inside the cool box to measure internal air temperature, one probe was inserted into the fish core to monitor flesh temperature, and one sensor was positioned outside the box to record ambient room temperature. This arrangement allowed continuous monitoring of the thermal gradient between the external environment and the internal storage space. At the start of each test, 10 kg of ice was placed inside the cool box

together with the fish sample, maintaining a consistent ice-to-fish ratio as defined in the experimental design. Temperature recording commenced immediately after the ice was loaded into the box and continued for 12 hours.

Temperature measurements were taken at 30-minute intervals throughout the observation period. During testing, particular attention was given to monitoring the rate of fish temperature increase and the temperature difference between the interior and exterior environments. Observations continued until the completion of the 12-hour test duration, including the phase when significant ice melting occurred.

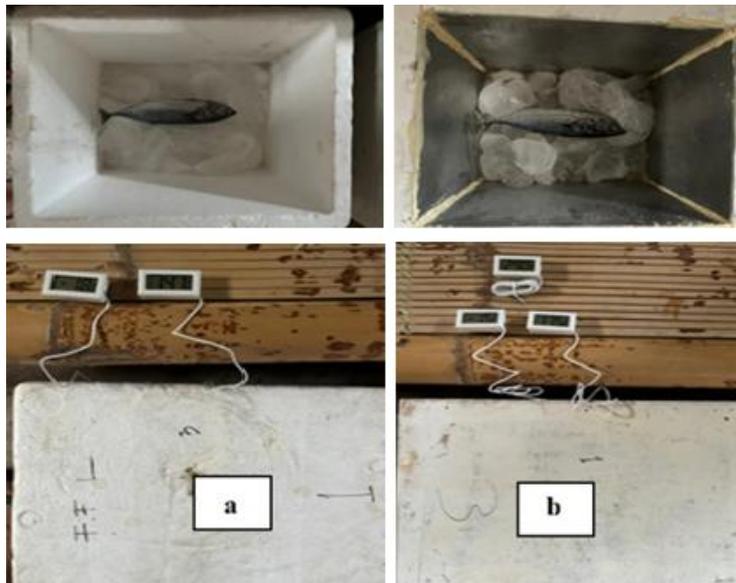


Figure 5. Experimental testing setup of the cool boxes: (a) Control cool box with factory-made expanded polystyrene (EPS); (b) Cool box insulated with Nipah palm fiber composite reinforced with polyurethane and aluminum reflective plate.

4. Discussion

4.1 Analysis of Insulation Performance and Thermal Resistance

Insulation performance is measured by how effectively a material inhibits heat transfer from the external environment into the cool box. In this study, the hybrid insulation system in Cool Box 3 consisting of palm fiber (Nipah), polyurethane, and aluminum foil demonstrated superior thermal resistance. Aluminum foil plays a critical role due to its very low emissivity, acting as a radiant barrier. The outer layer reflects environmentally radiant heat, while the inner layer slows down the heat radiated from the walls toward the product. To measure the effectiveness of the coolbox, the average rate of increase in fish temperature is:

$$\begin{aligned} \text{Rate of Fish Temperature Increase} &= \frac{\Delta T_{fish}}{\Delta t} \\ &= \frac{T_{final} - T_{initial}}{t} \\ &= \frac{0.4^{\circ}\text{C} - (-1.6^{\circ}\text{C})}{12 \text{ h}} \end{aligned}$$

$$= \frac{2.0^{\circ}\text{C}}{12 \text{ h}} = 0.167^{\circ}\text{C/h}$$

However, the experimental data suggests that the thermal resistance provided by the 3.5 cm thick palm fiber is the more dominant factor compared to the aluminum foil used in sawdust treatment. Cool Box 3 maintained an average internal temperature of only 7°C after 12 hours, significantly outperforming local Styrofoam standards. This is in line with a 2023 study [12], which noted that high-density natural fibers create micro-air cavities that effectively trap heat. With a temperature rise rate of only 0.167°C/hour, this biocomposite exhibits a competitive R-value (thermal resistance) compared to other natural insulators such as coconut fiber or hemp.

The experimental data reveals a clear hierarchy in thermal efficiency across the three tested models. While all boxes started at similar internal conditions, their ability to repel ambient heat varied based on the insulation material's density and reflective properties.

Table 2. Comparative Thermal Performance After 12 Hours

Box ID	Insulation Material	Final Fish Temp (°C)	Temp. Increase (ΔT)	Warming Rate (°C/h)
Box 1	Control (Styrofoam)	4.8	+6.4	533

Box ID	Insulation Material	Final Fish Temp (°C)	Temp. Increase (ΔT)	Warming Rate (°C/h)
Box 2	Raw Nipah Fiber	2.1	+3.7	308
Box 3	Hybrid Nipah + Foil	0.4	+2.0	167

As shown in Table 2, Box 3 (Hybrid) achieved a warming rate nearly three times slower than the standard Styrofoam box (Box 1). Box 2, using only raw fiber, also showed superior performance to Styrofoam, proving that Nipah fiber's natural cellular structure is inherently more effective than low-density EPS.

4.2 Thermal Gradient and Heat Load Management

During the 12-hour observation, a large temperature gradient existed between the environment (averaging 28°C to 25.7°C) and the internal box temperature. Despite a

temperature difference (Delta T) of approximately 20°C, the insulation successfully withstood the heat load. The internal temperature rose minimally from 6.3°C to 7.7°C (+1.4°C). While the average internal temperature of 7°C indicates the cooling medium (ice) had begun to melt significantly, the system's ability to keep the fish temperature below 1°C (rising from -1.6°C to 0.4°C) is a critical achievement. This slow rate of heat transfer proves that the Heat Load managed by the palm-fiber insulator is very low, ensuring the thermal stability required for long-duration transport.

Table 3. Temperature Changes in Box 3

	Initial Temperature (12.00)	Final Temperature (24.00)	Temperature Change (ΔT)
Inside temperature	6,3°C	7,7°C	+1,4°C
Outside temperature	28°C	25,7°C	-2,3°C
Fish temperature	-1,6°C	0,4°C	+2,0°C

4.3 Implications for Fish Preservation in Maritime Chains

In the fisheries cold chain, maintaining temperatures below 4°C is crucial to inhibit the activity of histamine-producing bacteria and spoilage-causing microorganisms. Compared with previous research [13], Nipah-based isolation provided a more stable temperature gradient during simulated pumper boat operations. By keeping fish at near-freezing temperatures for 12 hours, this isolation method directly maintained the organoleptic quality (texture, odor, and color) of the catch. For traditional fishermen in the Sangihe Islands, this technology offers a practical solution to increase the market value of their catch by reducing post-harvest losses.

4.4 Material Durability and Structural Advantages

The advantages of Nipah fiber are not only thermal but also structural. The high lignin and silica content of Nipah fiber [14], provides natural resistance to the high humidity and salty conditions of maritime environments. Unlike conventional Styrofoam, which is brittle, non-biodegradable, and tends to absorb water over time (reducing its insulating value), the Nipah-polyurethane hybrid is more durable and sustainable. This lignocellulosic structure ensures that the cooler box remains functional for a longer period, providing a cost-effective and environmentally friendly alternative for small-scale fisheries.

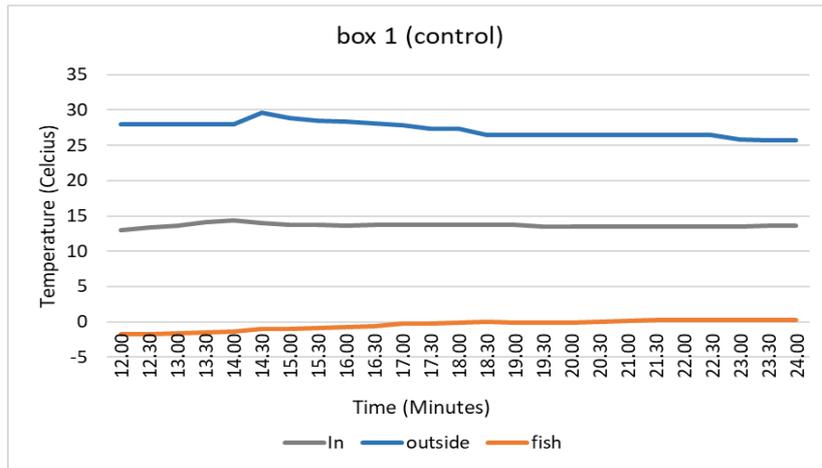
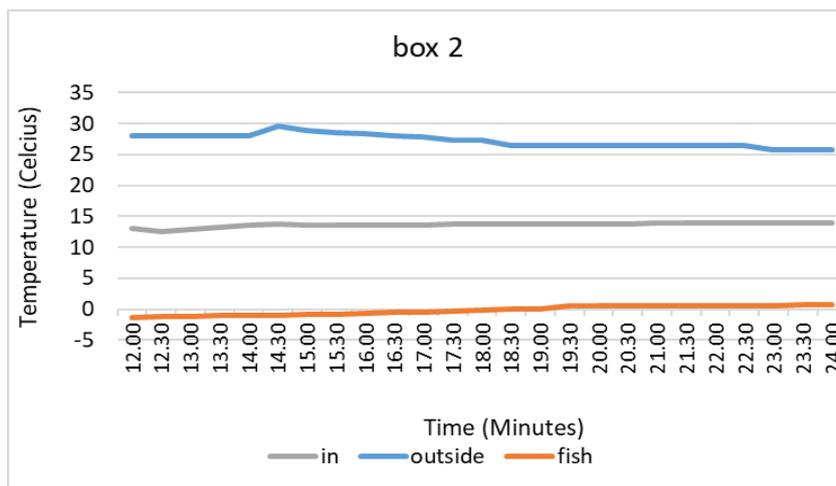
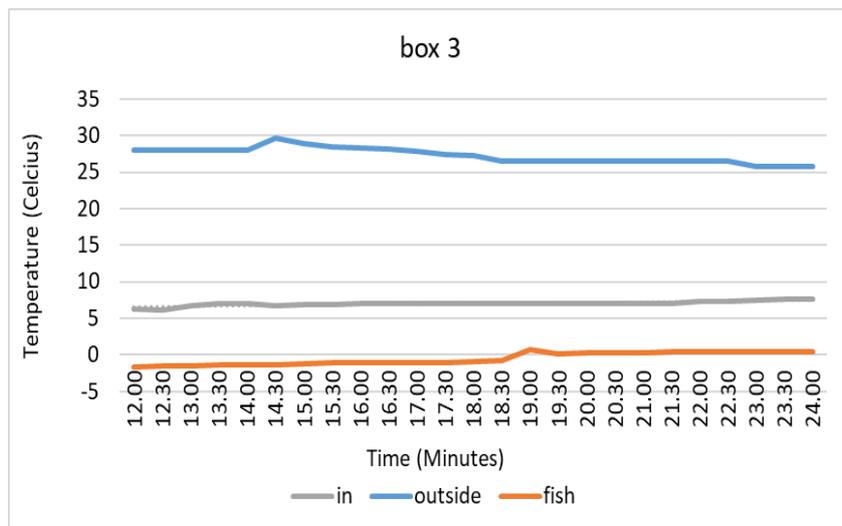


Figure 6. Temperature changes in the factory-made styrofoam box



Gambar 7. Coolbox 2 is insulated with palm fiber and polyurethane



Gambar 8. Cool box 3 is insulated with palm fiber, polyurethane and aluminum plates.

5. Conclusions

This study demonstrates that Nipah palm fiber (*Nypah fruticans*) waste serves as a highly effective and sustainable alternative insulation material for small-scale fisheries in the Sangihe Islands. The experimental results confirm that the hybrid configuration—utilizing compressed Nipah fiber integrated with a reflective layer (Cool Box 3)—significantly outperforms standard expanded polystyrene (EPS) boxes in thermal retention. The implementation of this bio-based insulation offers two strategic advantages: technically, it maintains a stable fish core temperature to preserve freshness throughout a 12-hour operational window; socio-economically, it reduces fishermen's dependence on costly and environmentally harmful synthetic polymers. Future research should focus on exploring natural binders to enhance the structural durability of the fiber composite against prolonged saltwater exposure in maritime environments.

Author contributions:

Author contributions: Author 1; Conceptualization and data analysis: Author 2; Correction of data analysis and correction of written language: Author 3 and 4 Correction of data analysis

Competing interests: There is no conflict of interest in writing this paper.

References

- [1] Sangihe in numbers. Overview of Capture Fisheries Production in the Sangihe Islands Regency. Central Statistics Agency of the Sangihe Islands Regency. 2021.
- [2] Taukhid, Daniel D, and S Realino B. Analysis of the Work of the Fish Vendor Refrigeration System. National Marine Journal, Vol. 9, No. 3. 2014.
- [3] Lungari F.F and Kumaseh E.I. The Relationship Between Main Size and Propulsion Power of Tuna Hand Line Pumpboats in Sangihe Islands Regency. Scientific Journal of Maritime Technology Vol. 12 No. 1. 2018.
- [4] Untung Budiarto, Kiryanto. Optimization of Fishing Hold Insulation Design of KM. Berkah 9 GT to Reduce Heat Transfer Rate. Ship: Journal of Marine Science and Technology, vol. 7, no. 3, Vol 7 No 3. 2012.
- [5] Metusalach, Kusmiati, Fahrul and Jaya I. The Effect of Fishing Methods, Handling Facilities and Fish Handling Methods on the Quality of Fish Produced. Jurnal IPTEK PSP Vo 1 No 1. 2014.
- [6] Kayoi M, Wanma J. F and Sadsoeitoeboen B.M.G. Technical Potential of Utilizing Nipah Leaf Stems and Their Mixture with Coconut Fiber for Making Medium Density Fiberboard. Journal of Forest Products Research Vol. 30 No. 3. 2012.
- [7] Roliadi H, Indrawan D.A, Pari G, and Tampubolon R.M. Technical Potential of Utilizing Nipah Leaf Stems and Their Mixture with Coconut Fiber for Making Medium Density Fiberboard. Journal of Forest Products Research Vol. 30 No. 3. 2012.
- [8] Amiruddin, Iskandar B. H, Murdiyanto B, Baskoro S. Mulyo. Density of Polyurethane Insulation on the Hold of Traditional Fishing Vessels in Pekalongan. Journal of Marine Fisheries, Vol. 4, No. 1. 2013.
- [9] Nasution P, Fitri S.P, Semin. Physical Characteristics of Coconut Fiber Composite as Fish Hold Insulator. Terubuk Fisheries Periodical Journal, Vol. 42. No. 2. 2014.
- [10] Kholis M N, Syofyan I, and Isnaniah. Study use powder as raw materials manufacturing saws insulator cooling box fish (coolbox) used by traditional fishermen. Neliti.com. pdf. <https://media.neliti.com/media/publications/202797-study-use-powder-as-raw-materials-manufa.pdf> [2] N. A. Nur Rahmat, W. Wahyuddin, and H. Palippui, "Shipbuilding Risk Analysis Using Consequence-Probability Matrix Technique", zonalaut, vol. 2, no. 3, pp. 1-6, Nov. 2014.
- [11] Ouakarrouch M, Bousshine S, Bybi A, Laaroussi N, Garoum M. 2022. Acoustic and thermal performances assessment of sustainable insulation panels made from cardboard waste and natural fibers. Applied Acoustics Journal, Volume 199.

- [12] Olivares-Marín M, Roman S, Gomez V, Escobar, Gonzalez C.M, Chaves-Zapata A, Ledesma B. 2023. Thermal Performance and Sound Absorption Capability of Water Hyacinth Stems-Based Materials. *Journal of Cleaner Production*, Vol 425.
- [13] Rahman M.M, Sikandar M.U, Chowdhury P, Roy S, and Khrystoslavenko O. 2025. Toward Sustainable Cold Chain Packaging: A Systematic Review of Insulating Materials and Green Alternatives for Temperature-Sensitive Logistic. *International Journal of Multidisciplinary Development, Perspectives & Innovation*, Vol 1.
- [14] Ghani R. S.M, Osman S.M, and Rani T. A.I.A. 2024. Exploring the potential of Nipah palm frond as sustainable raw material for eco-friendly particleboard production. *Journal Cleaner and Circular Bioeconomy*, Vol 8.